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Final Report for Low Pressure Tests of the CPU-400 Pilot Plant

Combustion Power Co, Inc, Menlo Park, Calif

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FINAL REPORT FOR LOW PRESSURE TESTS OF THE CPU-400 PILOT PLANT

by

Combustion Power Company, Inc.
1346 Willow Road
Menlo Park, California 94025

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This report presents the progress made during the component design phase of a program to develop an economical and environmentally safe waste-energy system known as the CPU-400. It discusses the hardware development and low pressure testing performed to evaluate CPU-400 operational characteristics in a large scale pilot plant. This work was performed as a prerequisite to final high pressure testing of the pilot plant facility.

Significant accomplishments made during this contract period included: the final procurement and testing of hot gas system components such as the full scale vertical combustor, three particle separators, and ash removal equipment; the final design and procurement of a computerized process control system; the procurement of a turbo-electric system, including the completion of all design required for its incorporation into the pilot plant; the completion of a survey of gas turbines for the prototype plant; and the successful performance of long duration, low pressure testing of all components integrated into the pilot plant system. Other work accomplished during the contract period included the quantitative and qualitative analyses of off-gases from the solid waste-fired combustor, the testing of a subscale granular filter, and the improvement of the solid waste processing systems throughput rate.

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Fluidized Bed Processors		Solid Waste	10/A
Combustion*	Shredders	Air Classification	13/H
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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the pollutional impact on our environment and even on our health often requires that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

Since 1967, the EPA has supported the development of the CPU-400, a system for converting waste directly into electrical energy. This report describes the progress made during the component design phase of the program. This report will be of special interest to those involved in the design, construction, and testing of waste-to-energy systems.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report presents the progress made during the component design phase of a program to develop an economical and environmentally safe waste-energy system known as the CPU-400. It discusses the hardware development and low pressure testing performed to evaluate CPU-400 operational characteristics in a large scale pilot plant. This work was performed as a prerequisite to final high pressure testing of the pilot plant facility.

Significant accomplishments made during this contract period included: the final procurement and testing of hot gas system components such as the full scale vertical combustor, three particle separators, and ash removal equipment; the final design and procurement of a computerized process control system; the procurement of a turbo-electric system, including the completion of all design required for its incorporation into the pilot plant; the completion of a survey of gas turbines for the prototype plant; and the successful performance of long duration, low pressure testing of all components integrated into the pilot plant system. Other work accomplished during the contract period included the quantitative and qualitative analyses of off-gases from the solid waste-fired combustor, the testing of a subscale granular filter, and the improvement of the solid waste processing system throughput rate.

Based on test results, it is concluded that the pilot plant is ready for turbine integration and high pressure testing. Combustion efficiency has exceeded design requirements and gas sampling analyses have indicated that present pollution control methods have met or exceeded all known pollution control requirements.

This report was submitted in fulfillment of Contract Number 68-03-0054 by the Combustion Power Company, Inc., under the sponsorship of the Environmental Protection Agency, Office of Research and Development, National Environmental Research Center, Cincinnati, Solid and Hazardous Waste Research Laboratory. Work was completed as of January 1973.

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SECTION I

CONCLUSIONS

Shredding and air classification operations on municipal solid waste produce a fuel form having very satisfactory physical properties for energy recovery through combustion in a fluidized bed reactor. A solid waste handling subsystem with reliable components has been developed and extensively operated.

The vertical fluidized bed combustor has been tested and proven to be a highly efficient, easily fed, readily controlled reactor of simple design that is capable of utilizing low quality fuels.

Test results of low pressure operation of the waste-fired vertical fluidized bed combustor show an average combustion efficiency of 99 percent.

Sixteen mesh silica beach sand is an acceptable starter bed material. The inert content of typical solid waste provides a natural bed makeup material that leads to a satisfactory steady state bed composition. As a result, the need for elaborate bed maintenance or anti-elutriation devices is minimized if not eliminated.

Test results to date show no problem with fluidized bed residue buildup. Relatively large metal and inert particles entering the active bed experience gradual oxidation or attrition to typical bed size particles and eventually are elutriated to be collected by particle separators. No bed material agglomeration is experienced in the 1270° F to 1450° F bed temperature range.

Gas phase combustion above the fluidized bed has been reduced to acceptable values without resorting to undesirable remedies such as extensive internal bed structures, numerous fuel feed points, deeper bed, multistage combustors, etc.

Combustor freeboard and exhaust system deposit problems due to the aluminum content of solid waste have been solved.

In low pressure testing such as conducted to date, problems of long term inertial separator performance degradation have been encountered due to tube plugging, particularly in the final stage with very fine hot flyash. Remedial development work will continue at the more promising high pressure conditions associated with integration into the gas turbine cycle.

Exhaust gas sampling instruments indicate that the pollution control effort required for the gaseous components of the CPU-400 process can be expected to be minimal.

No evidence of serious hot gas system material corrosion or erosion problems has been found.

The capability of the manual and computerized control systems to adequately control low pressure pilot plant operation was successfully demonstrated. No problems are foreseen for control of high pressure pilot plant operation.

SECTION II

INTRODUCTION

GENERAL

Combustion Power Inc. of Menlo Park, California has successfully demonstrated the completion of component design and low pressure testing for the CPU-400 pilot plant. The CPU-400 is a gas turbine-combustion concept that cleanly and cheaply burns municipal solid waste at elevated pressure for the recovery of energy in the form of electrical power while recovering valuable secondary materials in the form of metals and glass. The electrical energy that can be generated for the projected 1975 per capita solid waste production of 3.3 pounds per day is 14.2 percent of the combined electrical energy consumed by American households and commercial establishments, or 8.3 percent of the total electrical energy production of the United States that is projected for 1975.*

The expected increase in solid waste generation, together with the capability of the CPU-400 to burn fast replenishable combustible materials such as wood, and the critical need to develop new inexpensive energy sources in order to lessen this country's dependence on oil, gives the CPU-400 concept great growth potential as an important ancillary source of energy generation.

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*Values calculated from data presented in EPA Publication No. SW-122[1]

The work described in this report pertains to tasks defined in contract No. 68-03-0054 and was performed during the period from June 30, 1971, to April 30, 1973, with funds provided by the United States Environmental Protection Agency, Office of Research and Development, Industrial Environmental Research Laboratory, Cincinnati, Ohio. It was follow-on work to contract PH 86-68-198 which was completed on December 31, 1971.

OBJECTIVES

The ultimate objective of the CPU-400 project was to successfully demonstrate the operation of a prototype plant that will cleanly and efficiently dispose of solid waste at a fraction of the total cost of current disposal methods while generating electrical power. The immediate objective of the work performed during the contract period covered by this report was to successfully demonstrate the pilot plant component development and readiness for turbine integration through the performance of extensive long duration testing.

ACHIEVEMENTS

Important achievements made during the contract period included: Final hardware procurement and low pressure testing of the fluid bed reactor, three stages of particle separators, ash removal systems, process control computer, instrumentation, gas analysis equipment, 1/20 scale model testing, and the procurement and design for integration of the turbo-electric system including the compressor/turbine/generator set, switch gear, and load bank. This work culminated in the successful demonstration of the integrated operation of the solid waste handling system, hot gas system, and automatic process control system at precisely controlled temperature conditions for 48 hours of continuous operation. This test completed the scheduled low pressure testing and verified system readiness for initiation of high pressure testing.

During the low pressure, high temperature (1450 °F third stage outlet temperature) testing, multitube cyclone separator tube plugging problems and collecting hopper ash unloading problems were encountered. Investigations with the separator modules and full scale units are continuing to provide a successful solution without compromising separation efficiency. The future higher pressure testing operation will be beneficial to ash unloading via blowdown, will provide a higher separator tube differential pressure, and will raise the Reynolds number above the present level of 2000 under which tube operational problems can be predicted. In addition, an investigation of various separator internal devices has indicated their suitability for keeping individual tubes from plugging.

Work is presently in progress to integrate the turbo-electric system with the hot gas system and process controls, and to ready the pilot plant for high pressure testing in which the energy recovery concept (the generation of electrical power with an open gas turbine cycle using solid waste as the only fuel), will be demonstrated. This work is being performed in accordance with contract PH 86-03-143 and is now scheduled for completion in 1975.

PILOT PLANT DESCRIPTION

The present CPU-400 pilot plant (Figure 2-1) consists of four primary systems: the solid waste handling system, the hot gas system, the turbo-electric system, and the process control system.

The solid waste handling system prepares the solid waste material for combustion. This includes shredding, separation of the shredded material into combustible and inert components, storing the combustibles until ready for use, and metering the solid waste to the combustor. Unprocessed municipal waste is initially loaded on the shredder conveyor by a skip loader. The conveyor modulates the feed to the shredder based upon electrical loading of the shredder motor. After shredding, the material is fed to the air classifier where the light, combustible materials are pneumatically lifted and transported to an Atlas storage unit while the heavy, inert materials drop out for subsequent separation and recovery. Metering of the prepared solid waste fuel is accomplished through a variable speed, servo controlled outfeed conveyor in the Atlas storage unit and variable speed transfer and weighing conveyors which transfer the processed solid waste to airlock feeder valves. The airlock feeder valves admit the solid waste to pressured feed pipes which route the material to the combustor fluidized bed.

The hot gas system consists of the solid waste combustor, 3 particulate removal stages, ash removal equipment, and interconnecting piping and valving. After the solid waste is introduced into the combustor it is burned and the resulting hot gases are then cleaned of suspended solid

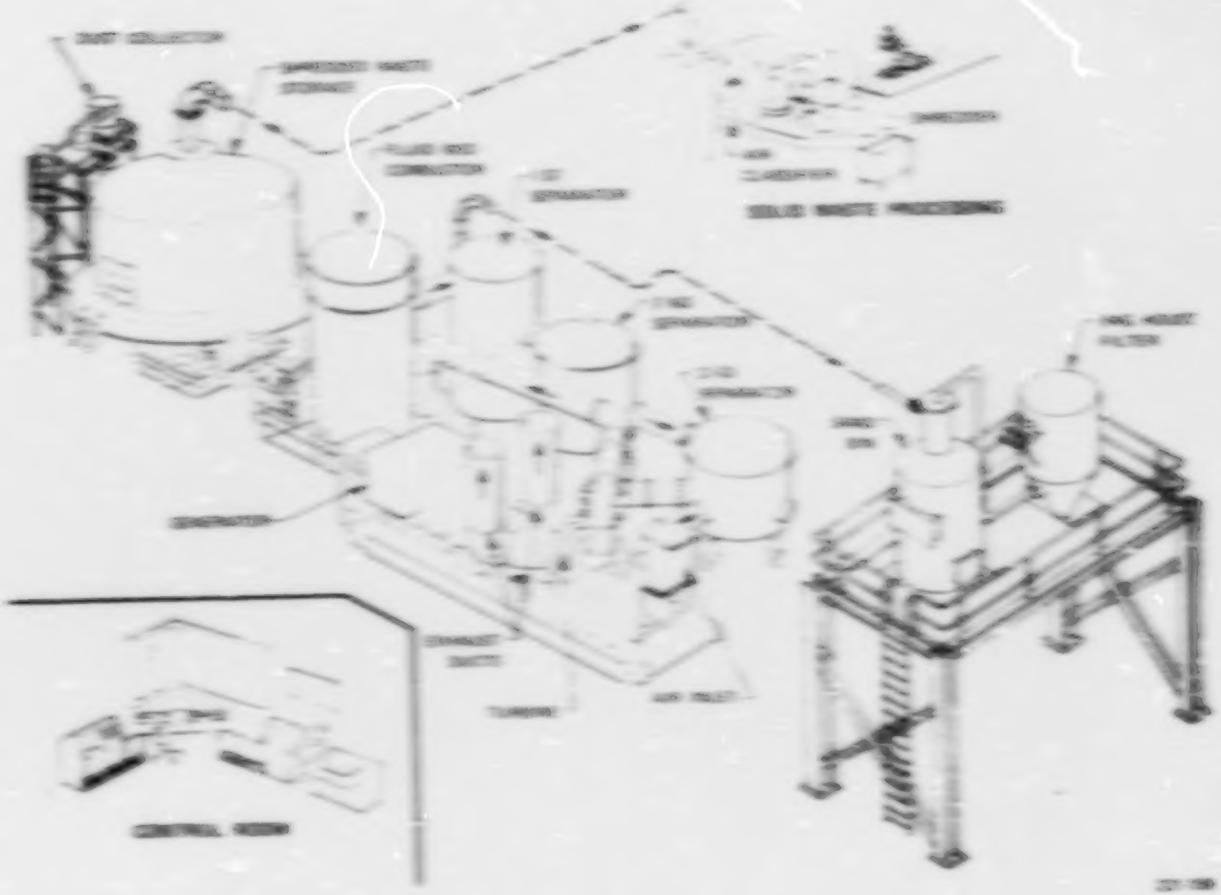

DUST COLLECTOR
EMERGENCY WASTE STORAGE
FLUID BED COMBUSTOR
1ST SEPARATOR
SHREDDER
AIR CLASSIFIER
SOLID WASTE PROCESSING
2ND SEPARATOR
3RD SEPARATOR
FILTER
GENERATOR
EXHAUST DUCTS
TURBINE
AIR INLET
CONTROL ROOM

Figure 2-1 CPU-400 Pilot Plant

material in the three stages of separation. Residue material is removed from the particle separator collection hoppers by pneumatic transport to external collection points.

The turbo-electric system, currently being installed, consists of a gas turbine, a generator, switch gear, and a load bank. The compressor section of the turbine supplies the cold air for the solid waste combustor fluidization. The resulting hot gases, after being cleaned in the separators, are used to power the compressor turbine and the power turbine. The generator is driven by the power turbine and generates power which is subsequently controlled by the switch gear. The electrical energy output of this pilot plant system will be dissipated in a combination load and light bank. In the full scale system, the electrical power will be delivered to a customer for subsequent use in the municipality. In the low pressure configuration operated to date, the gas turbine compressor is replaced by a facility blower and exhaust gases are cooled by water spray. The blower also supplies fuel transport air to the fluidized bed.

The control system interacts with these systems to control their respective outputs in response to commanded set points. This system, which features analog controllers under the supervisory control of a digital process computer, also monitors numerous signals to provide data acquisition, logging, out-of-tolerance alarming, and status display functions.

SECTION III

HOT GAS SYSTEM

The Hot Gas System consists of all equipment required to produce and deliver to the turbine a controllable, cleaned, hot gas product. Included are a combustor, particle collection equipment, a material removal system, gas analysis equipment, and all connecting piping, gauges, meters, and related ancillary equipment. Several different configurations of this equipment were tested as new components were added to the system. Comprehensive details of the major components or subsystems designed and fabricated under this contract are outlined in the four major areas that constitute this section. These are: "The Design and Development of the Vertical Combustor and Support Equipment"; "The Design and Development of Particle Collection Equipment"; "The Design and Development of the Residue Removal System"; and "The Determination of Off-Gas Composition of a Fluid Bed Combustor Burning Municipal Solid Waste".

DESIGN AND DEVELOPMENT OF THE VERTICAL COMBUSTOR AND SUPPORT EQUIPMENT (TASKS LP-12A and LP-12B)

The vertical combustor was designed, built, and tested in the pilot plant system for use with the Mid-Continent/S[illegible]ton TA-1500 gas turbine. It was the result of exploratory development testing with the horizontal combustor and provided an updated pilot plant operating philosophy which was evolved since inception of the original design. A cross-sectional view of the vertical combustor is shown in Figure 3-1. The vertical combustor, as installed in its pit within the existing facility, is shown in Figure 3-2.

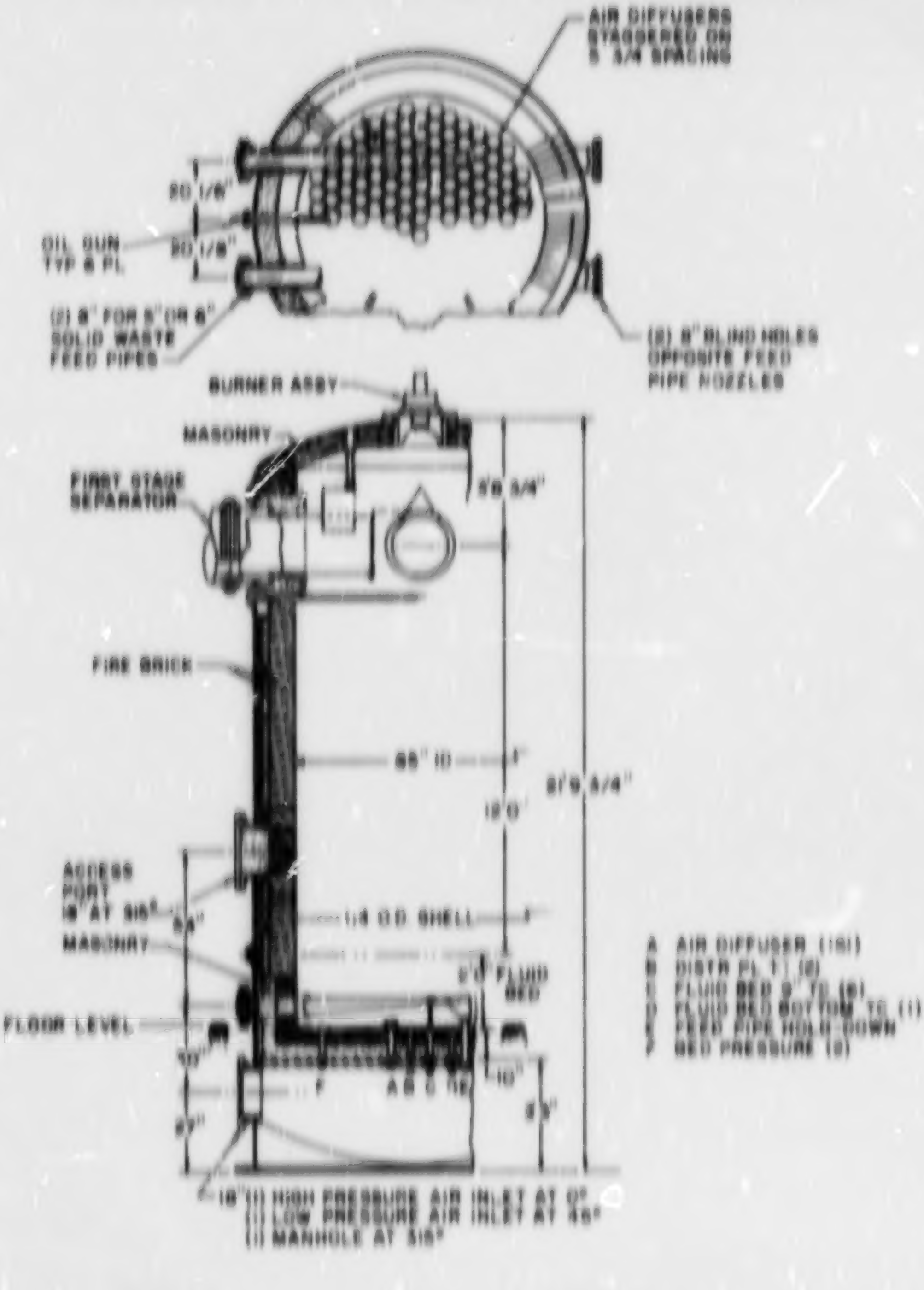

AIR DIFFUSERS STAGGERED ON 5 3/4 SPACING
20 1/8"
20 1/8"
OIL GUN TYP 8 PL
(2) 8" FOR 5" OR 6" SOLID WASTE FEED PIPES
(2) 8" BLIND HOLES OPPOSITE FEED PIPE NOZZLES
BURNER ASSY
MASONRY
FIRST STAGE SEPARATOR
5'8 3/4"
FIRE BRICK
66" ID
12'0"
21'5 3/4"
ACCESS PORT 18" AT 315°
54"
1/4 OD SHELL
MASONRY
2'0" FLUID BED
FLOOR LEVEL
10"
10"
F
A B C D
27"
2'3"
18" (1) HIGH PRESSURE AIR INLET AT 0°
(1) LOW PRESSURE AIR INLET AT 45°
(1) MANHOLE AT 315°
A AIR DIFFUSER (151)
B DISTR PL T/C (2)
C FLUID BED 9" TC (8)
D FLUID BED BOTTOM TC (1)
E FEED PIPE HOLD-DOWN
F BED PRESSURE (2)

Figure 3-1 Vertical Combustor

Figure 3-2 Vertical Fluid Bed Combustor Assembly

Improvements Over the Horizontal Combustor

The vertical combustor system was designed to minimize or eliminate certain problem areas identified during testing with the horizontal combustor.

One of the principal problems of the horizontal combustor, shown in Figure 3-3, was elutriation of the bed material from the combustor unit. The installation of bubble screens to reduce surface explosions of sand, and various baffles and inertial devices in the combustion chamber, were ineffective due to the high temperature clinker formation and the violence of sand explosions, which deformed or otherwise caused the devices to fail. Also, since the freeboard area decreased in size toward the top of the vessel, sand particles were entrained in the flow stream and pneumatically transported out of the chamber at a rate higher than that at which sand was normally introduced with the solid waste stream. This necessitated the addition of bed material by mechanical means. Internal configurations evaluated during the testing of the horizontal combustor are depicted in Figure 3-4.

In the vertical combustor design, elutriation is reduced by providing a high freeboard volume in which the average gas velocity is approximately 6 ft/sec-below the terminal velocity of nominal bed material at turbine temperature and pressure conditions. In addition, the vertical combustor design reduced the tendency of the feedline air flow to direct sand particles towards the exhaust port where they could be entrained into the exhaust gas stream and carried out of the combustor. The top cylindrical section of the combustor, which contains the exhaust penetration,

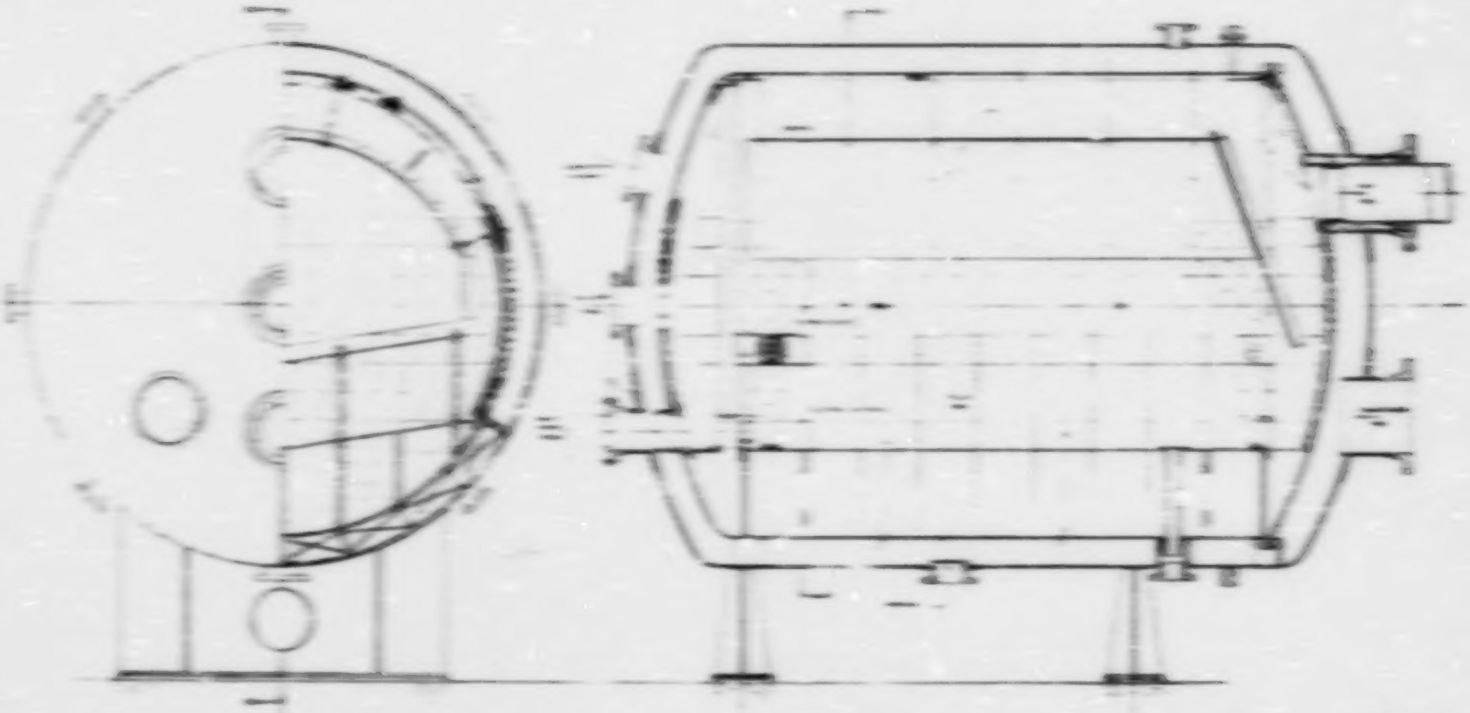


Figure 3-3 Horizontal Fluid Bed Combustor Assembly

Figure 3-4 Horizontal Combustor Internals

is designed to be removable with its insulation to permit increase of the freeboard height with minimum amount of rework.

A second problem encountered in the horizontal bed was that the height of the static bed was limited to 2 feet due to the proximity of the exhaust port. In the vertical unit bed depths up to 4 feet can be used to obtain a higher portion of the heat release within the active part of the bed, thus reducing heat release in the gas zone above the bed. The latter improves potential utilization of the chemical characteristics of bed materials in suppressing undesirable gas constituents such as SO_2 or HCl. Control of temperature differences between bed material and combustor exhaust could also be improved by the increased bed depths.

A third problem which the vertical combustor minimizes is heat loss. In the horizontal combustor, where the inner vessel would have been cooled with the turbine compressor air, a local outer wall temperature in the 600^0 F range would be anticipated for the 400^0 F compressor air at rated power, with resultant high heat loss through radiation and convection. The refractory thermal insulation of the vertical combustor will maintain a nominal skin temperature of 230^0 F. The refractory insulation and its high heat capacity also minimizes heat loss from the bed during static conditions (overnight shutdowns, maintenance cycles, etc), and permits normal system startup without sand heating after overnight shutdowns.

In the horizontal combustor, the preheat burner had to be located on the centerline of the concentric vessel due to differential thermal expansions. This resulted in contact between the burner flame and top layer of the fluid bed material resulting in incomplete local combustion and fusion of the adjacent sand layer. This problem was resolved by the vertical combustor, which permits the use of a high capacity burner for quick sand heatup operation within two hours. It is located in the top pressure dome of the vessel at a maximum distance from the sand. The internal view of the combustor, Figure 3-5, shows the burner block at the center of the top dome and the exhaust pipe which extends into the freeboard. This allows complete combustion and mixing of the burner combustion products and burner excess air or/or to hot gas penetration into the bed, and minimizes burner fouling during fluidized operation.

Improvements in the fuel and air feed systems were also incorporated into the vertical combustor. In the horizontal unit, feedline penetration had to be parallel to the combustor centerline; in the vertical unit, penetration around the entire circumference at any elevation is possible. The round, flat, distributer plate in the vertical unit with the 161 individual sintered metal screen diffusers (Figure 3-6) also improves distribution of fluidizing air over the dihedral-rectangular plate in the horizontal bed. Internal leakage in thu horizontal unit, which allowed bypass of the bed by some of the fluidizing air, was entirely deleted by the welded construction of the vertical combustor.

Vertical Combustor Description

The vertical combustor is a 9½ foot outside diameter cylindrical carbon steel pressure shell with dished heads insulated from the hot gases by refractory insulation. The fluid bed is supported by a flat carbon

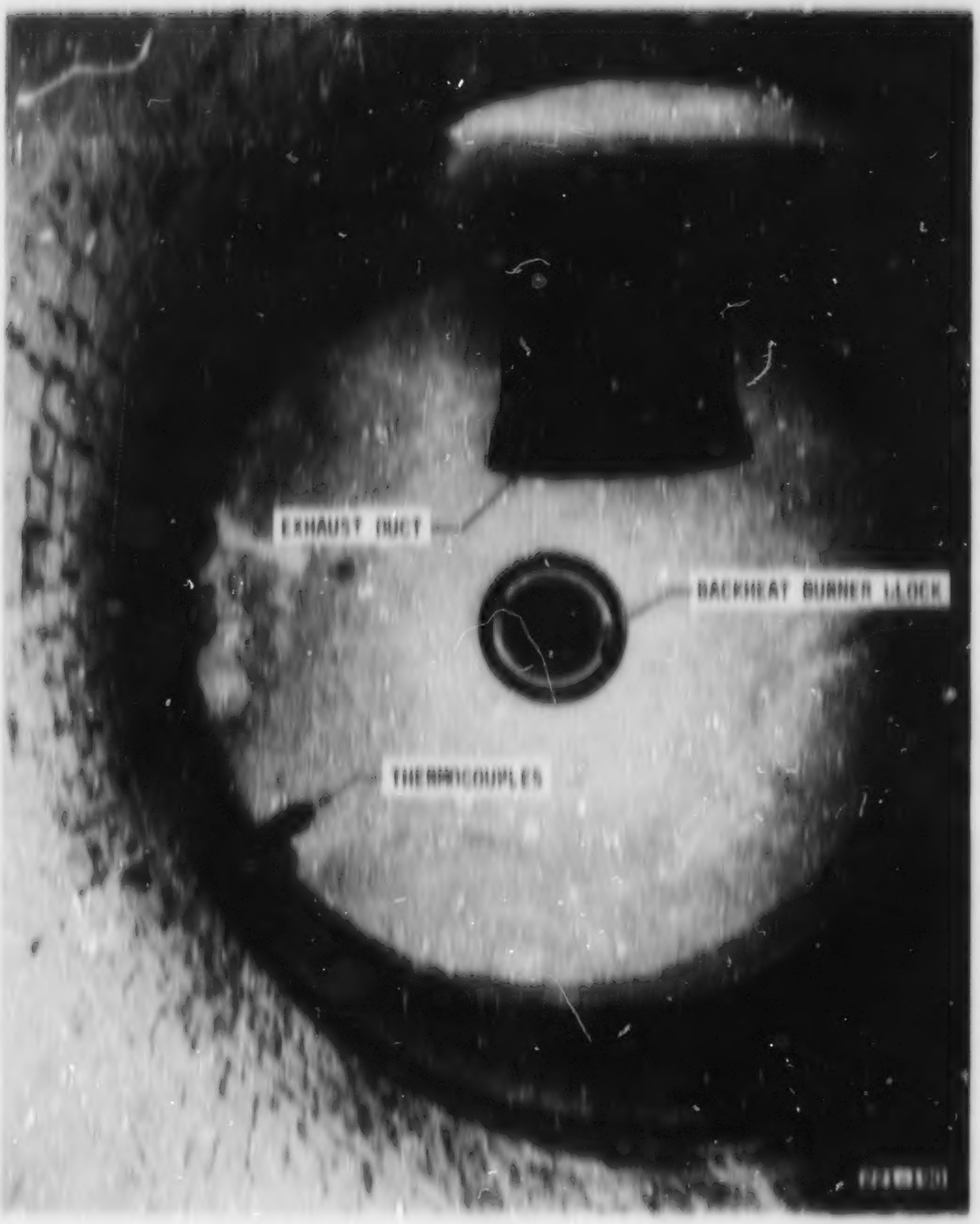

EXHAUST DUCT
BACKHEAT BURNER BLOCK
THERMOCOUPLES

Figure 3-5 Combustor Exhaust and Backheat Burner Ports

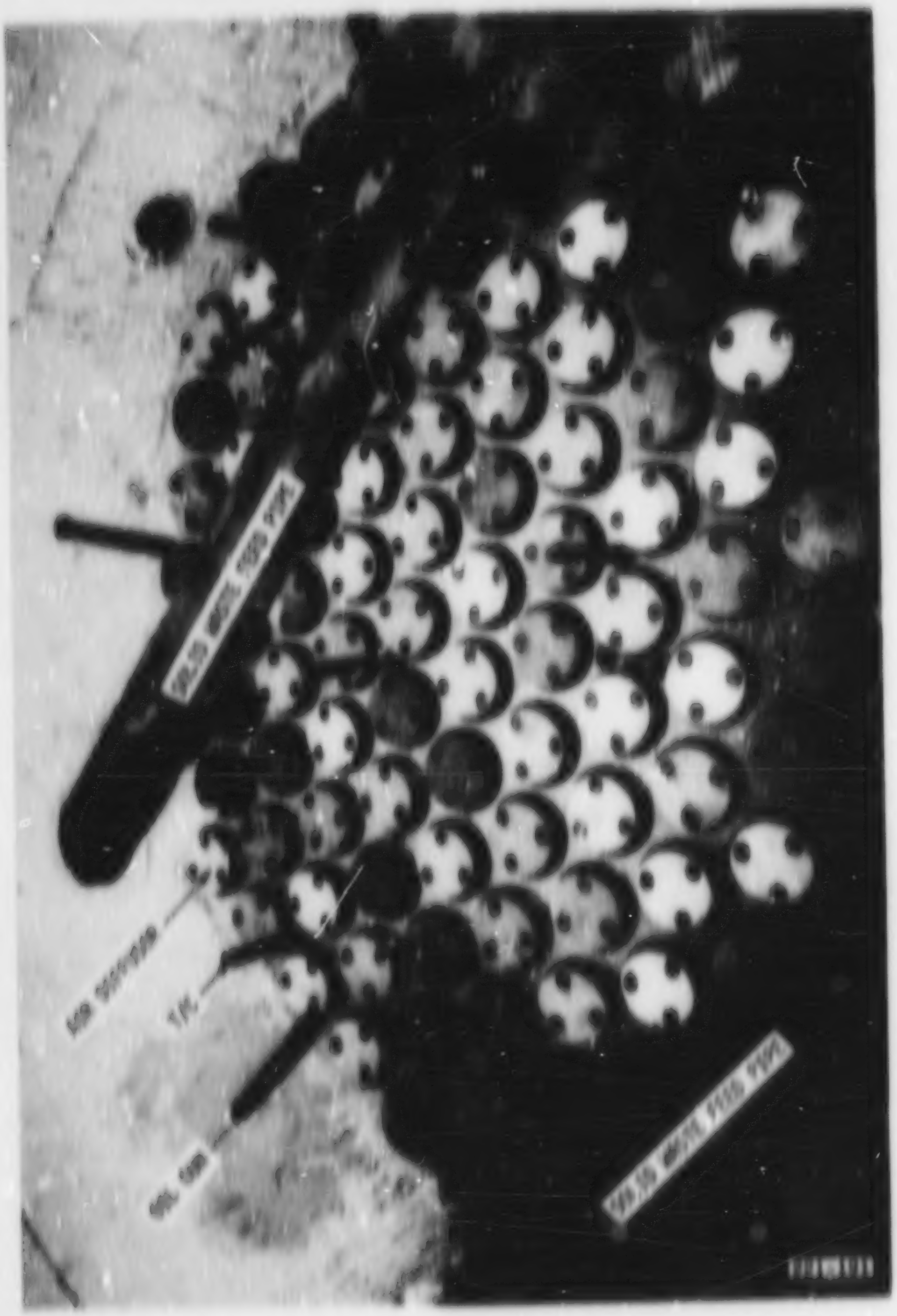
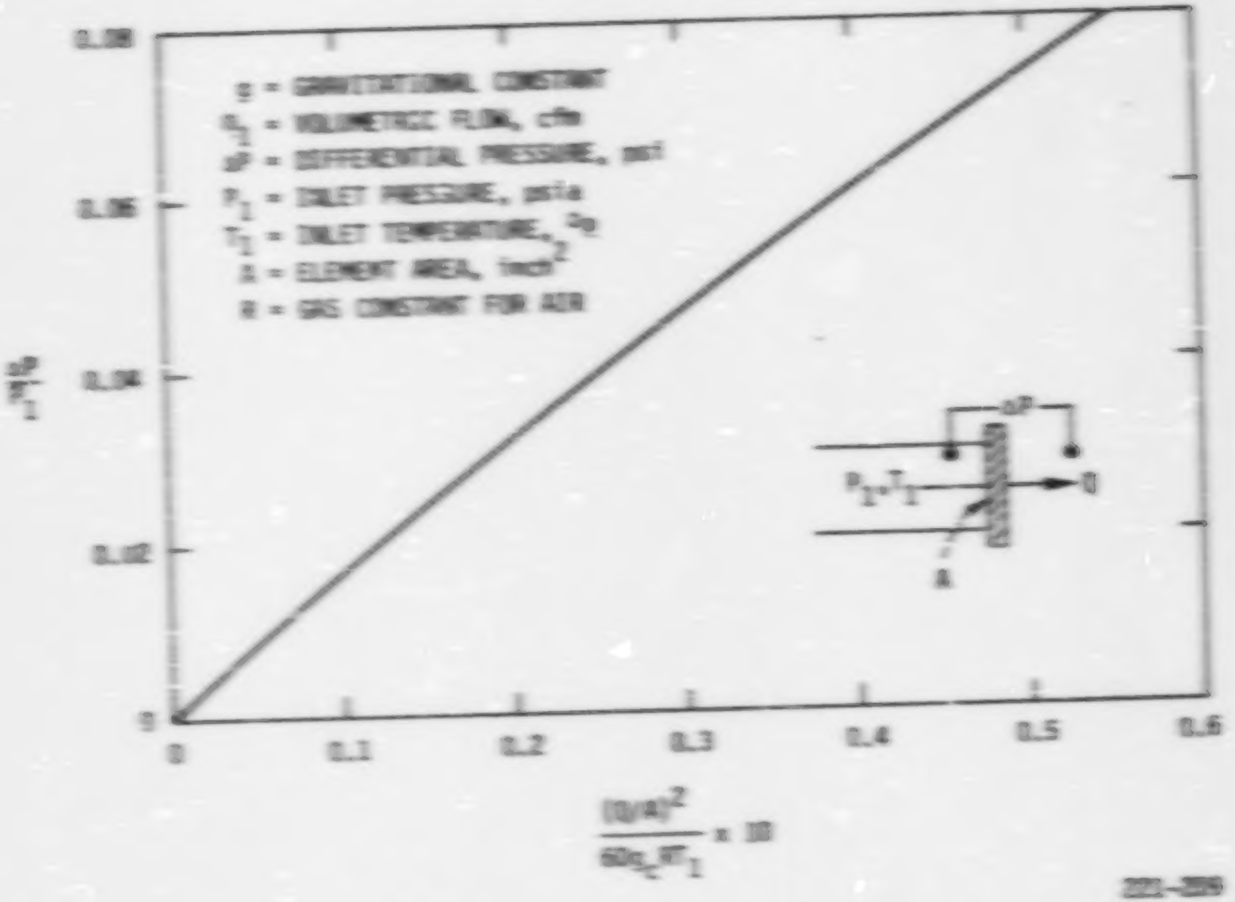


Figure 3-6 Air Distributors and End Feedpipes

steel plate also insulated and welded to the pressure shell. Penetrating the insulated plate are 161 2-inch pipes that connect to sintered wire stainless steel diffusers and seven 1-inch pipes for thermocouples or pressure tap installations. Figure 3-7 shows the normalized diffuser pressure/flow characteristics. The shell has penetrations into the fluid bed for two solid waste feed pipes and six oil injection points. Two additional nozzles were provided in the pressure shell to allow future growth to four solid waste feed points.

Located on top of the combustor is the oil burner used to preheat the bed material under low pressure conditions. This unit, rated at 1,500 cfm, maintains the output gas at 1600° F over a 4:1 turndown ratio. The remaining 3,300 cfm from the rotary positive displacement blower flows into the air plenum below the combustor distributor plate. With the outlets from the third stage separator blanked off, the combustion gases produced by the burner are thus forced to flow through the sand where they are mixed with the blower excess air in the plenum below the distributor plate and dumped overboard through the 12-inch duct (valve 005) that branches off the high pressure air supply line. The piping schematic to the combustor, Figure 3-8, has been included for valve and valve nomenclature definition.

The preheat burner, a schematic of which is shown in Figure 3-9, contains a propane secondary gas ignition system which provides a positive means for igniting the diesel fuel. The propane is ignited by a spark which is on for approximately 15 seconds. As soon as oil ignition is



221-289

Figure 3-7 Normalized Flow Characteristics

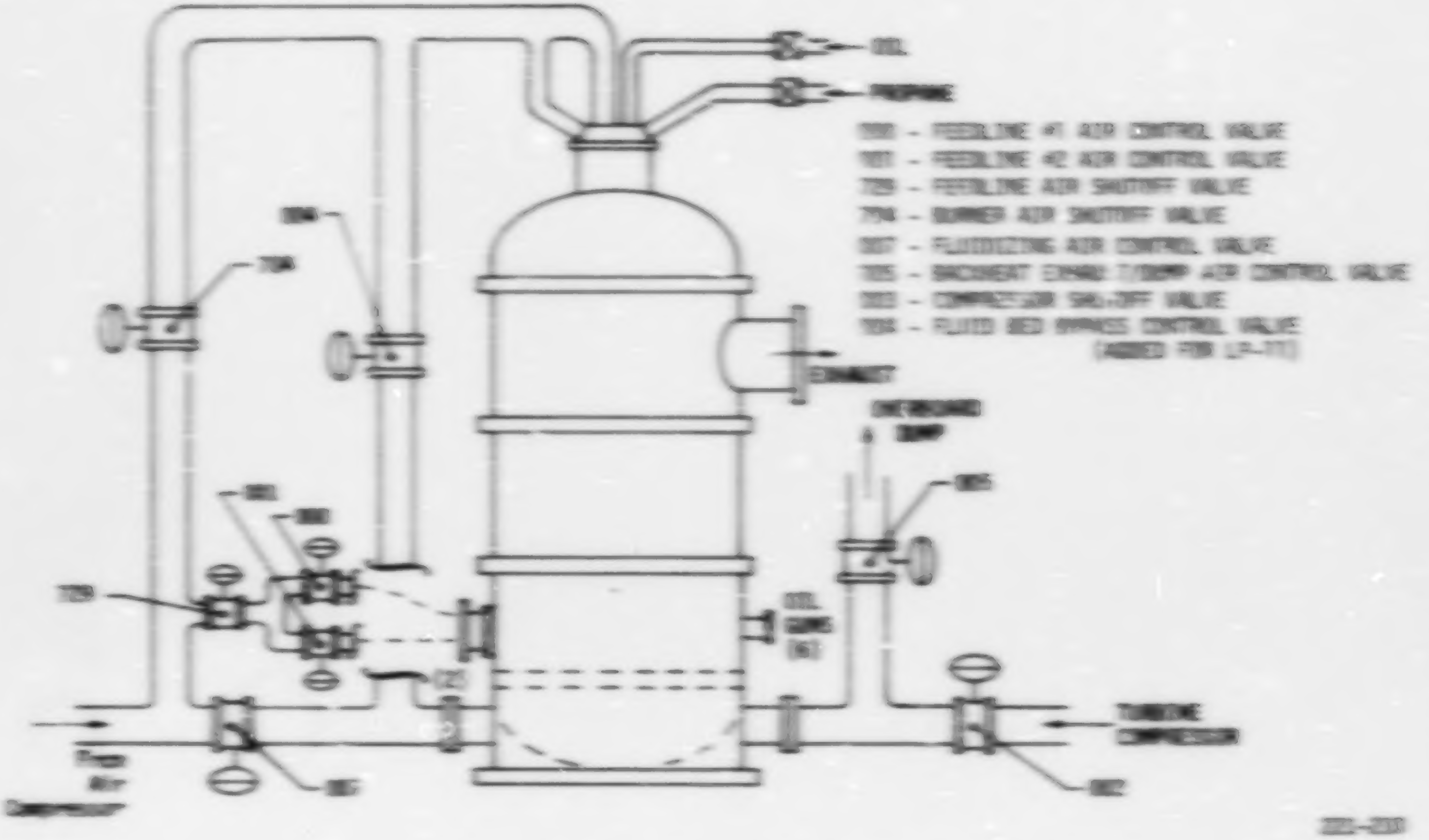
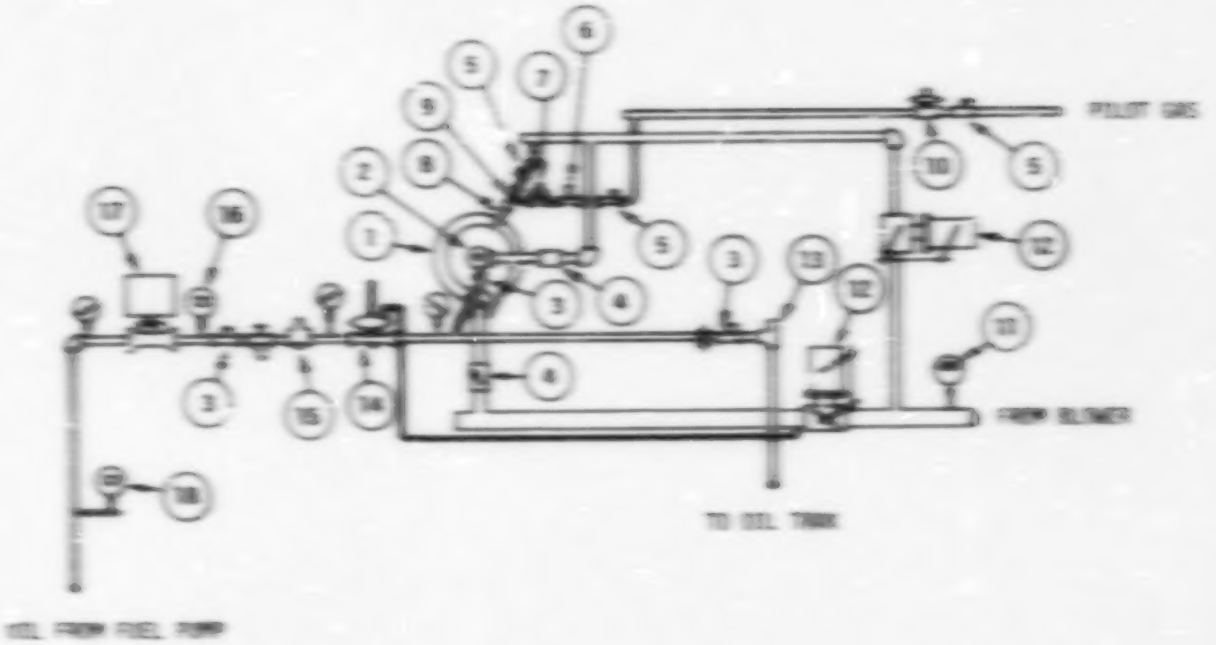

OIL
PROPANE
800 - FEEDLINE #1 AIR CONTROL VALVE
801 - FEEDLINE #2 AIR CONTROL VALVE
729 - FEEDLINE AIR SHUTOFF VALVE
794 - BURNER AIR SHUTOFF VALVE
806 - FLUIDIZING AIR CONTROL VALVE
805 - BACKHEAT EXHAUST/DUMP AIR CONTROL VALVE
802 - COMPRESSOR SHUTOFF VALVE
804 - FLUID BED BYPASS CONTROL VALVE
(ADDED FOR LP-77)
794
804
EXHAUST
OVERBOARD
DUMP
801
800
805
729
OIL
GUNS
(6)
(2)
TURBINE
COMPRESSOR
Plant
Air
Compressor
806
802
221-233

Figure 3-8 Vertical Combustor Air Valve Definition


PILOT GAS
FROM BLOWER
TO OIL TANK
OIL FROM FUEL PUMP
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

1. CONVECTO-FLAME BURNER (M-60)
2. OIL METERING VALVE (INCLUDED IN BURNER)
3. MANUAL OIL VALVE (M-107)
4. MANUAL BUTTERFLY VALVE (M-150)
5. MANUAL GAS COCK (M-150)
6. PILOT SOLENOID VALVE (M-507)
7. PILOT GAS GOVERNOR (P-80)
8. PILOT NOZZLE (P-80)
9. PILOT GAS/AIR MIXER (P-80)
10. PILOT GAS PRESSURE REGULATOR (M-023)
11. LOW AIR PRESSURE SWITCH (M-31)
12. MAIN AIR CONTROL VALVE (M-150 & M-200)
13. OIL RELIEF VALVE (R-312)
14. OIL [illegible] VALVE (R-320)
15. OIL PRESSURE REGULATOR (R-319)
16. HIGH OIL PRESSURE SWITCH
17. OIL SAFETY SHUT OFF VALVE
18. LOW OIL PRESSURE SWITCH

202-223

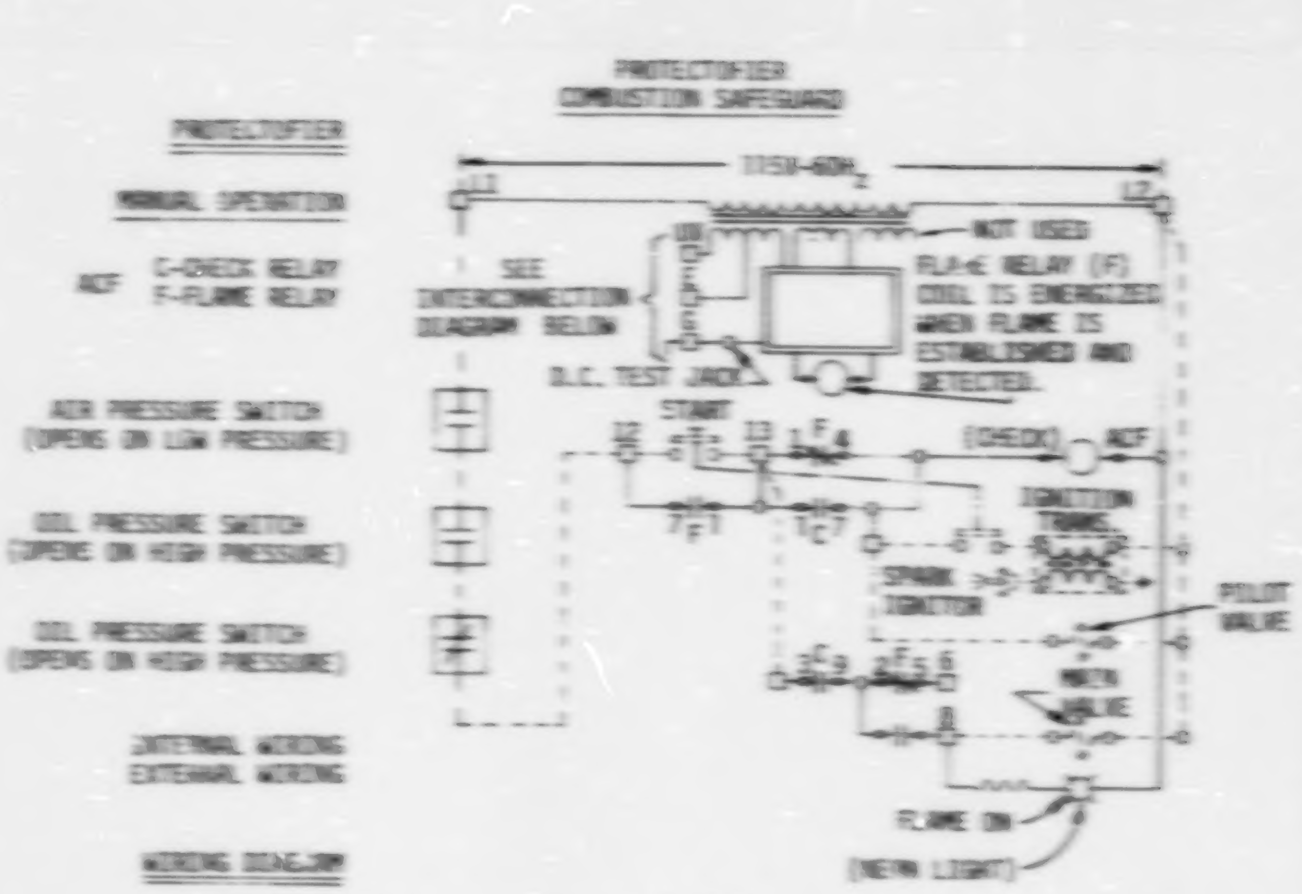
Figure 3-9 Burner System Schematic

obtained, the spark is then shut off to avoid ultraviolet interference with the flame detection system, illustrated in Figures 3-10 and 3-11. This system provides the input signal to the on/off valves and the ignition transformer, monitors system parameters, and shuts off the ignition and main burner valves in the absence of a flame sensed by an ultraviolet scanner.

The ducting to and from the combustor includes valving to control the air flow during the various operating modes of the combustor. During fluidization, a 12-inch butterfly valve (005) seals off the backheat exhaust duct and the combustor exhaust flows through the three stages of in-series particle separators. During low pressure tests, the gas leaving the last particle separator was exhausted directly into the atmosphere. During high pressure operation, the gas will be ducted into the turbine.

Fluidizing air for low pressure tests was supplied to the combustor through a 14-inch line coming from the rotary positive displacement blower. During high pressure tests the fluidizing air will be supplied through an 18-inch diameter line coming from the turbine compressor. Remotely controlled, air-operated valves (007 and 003, respectively) are located in these lines to isolate the inactive mode of operation. Inlet and outlet silencers were provided with the blower to reduce noise levels to acceptable limits.

Located over the combustor and particle separation units are monor hoists for use in assembly and disassembly of the two top sections of



PROTECTOFIER
COMBUSTION SAFEGUARD
PROTECTOFIER
MANUAL OPERATION
C-CHECK RELAY
ACF F-FLAME RELAY
AIR PRESSURE SWITCH (OPENS ON LOW PRESSURE)
OIL PRESSURE SWITCH (OPENS ON HIGH PRESSURE)
OIL PRESSURE SWITCH (OPENS ON HIGH PRESSURE)
INTERNAL WIRING
EXTERNAL WIRING
WIRING DIAGRAM
115V-60Hz
L1
L2
NOT USED
SEE INTERCONNECTION DIAGRAM BELOW
FLAME RELAY (F) COIL IS ENERGIZED WHEN FLAME IS ESTABLISHED AND DETECTED.
D.C. TEST JACK
START
12
13
F
4
7
F
1
1
C
7
(CHECK)
ACF
IGNITION TRANS.
SPARK IGNITOR
PILOT VALVE
MAIN VALVE
2
F
3
2
F
5
6
8
FLAME ON
(NEON LIGHT)

Figure 3-22 Flame Detection Schematic Diagram

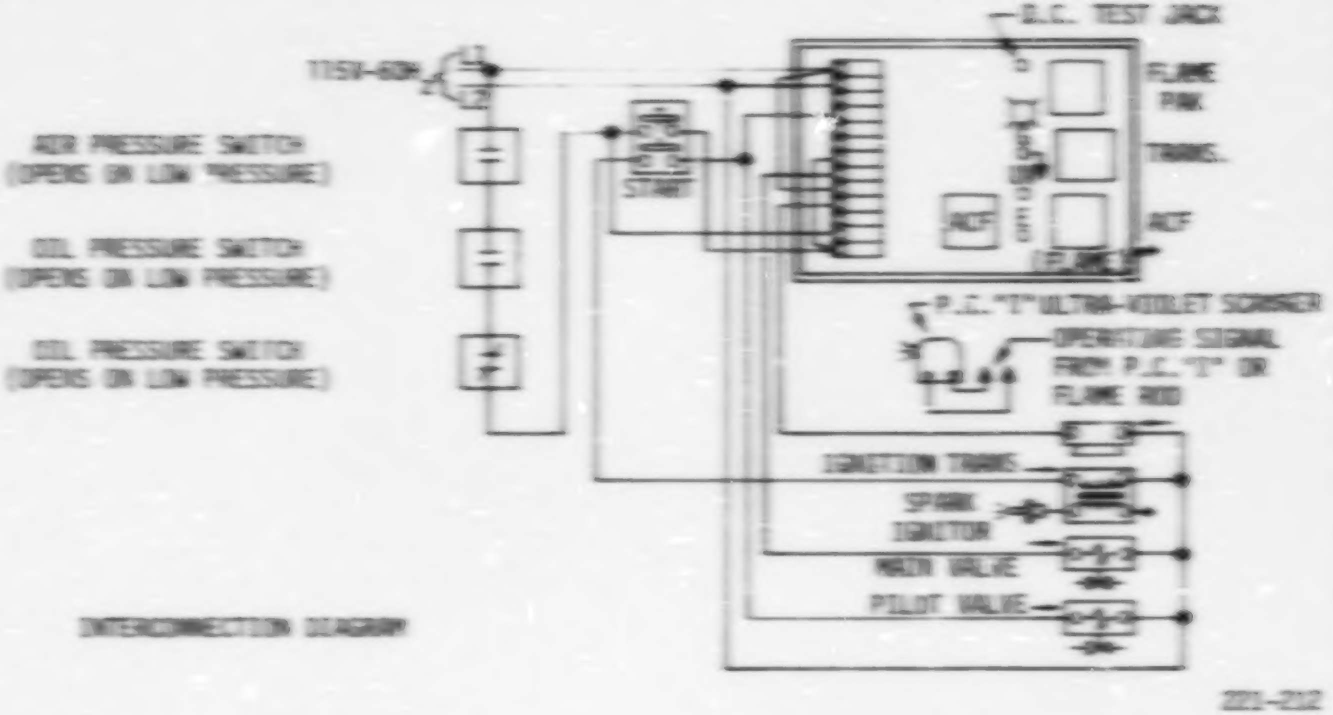

D.C. TEST JACK
115V-60Hz
L1
L2
FLAME PAK
TRANS.
ACF
ACF
FLAME
START
AIR PRESSURE SWITCH
(OPENS ON LOW PRESSURE)
OIL PRESSURE SWITCH
(OPENS ON LOW PRESSURE)
OIL PRESSURE SWITCH
(OPENS ON LOW PRESSURE)
P.C."T" ULTRA-VIOLET SCANNER
OPERATING SIGNAL
FROM P.C."T" OR
FLAME ROD
IGNITION TRANS.
SPARK
IGNITOR
MAIN VALVE
PILOT VALVE
INTERCONNECTION DIAGRAM
221-212

Figure 3-11 Flame Detection Interconnection Diagram

the combustor and for removal of the top sections of the separators during inspection cycles.

Six oil guns, similar in design to the units used in the horizontal combustor, were incorporated into the vertical combustor to permit fluidization combustion of auxiliary fuel. These guns are spaced around the periphery of the combustor and penetrate 12 inches into the bed. Each gun (Figure 3-12) includes mixing air and cooling air flow channels to keep the injection pipes clear of fluid bed material and diesel oil, which would otherwise crack under heat soak conditions and plug the piping. Oil is supplied to the guns through a 100 psi system for low or high pressure operation. Numerous access and work platforms were installed around the units at points where maintenance, inspection, or visual observation are to be accomplished.

After the refractory was installed and cured with the sand backheat burner, a series of checkout tests and hot tests were conducted. The combustor has provided trouble-free performance for over 150 hours of high temperature operation with solid waste fuel in satisfying contract test requirements. All design objectives were demonstrated. They included: (1) good fluidization under low air flow conditions; (2) fast 2-hour sand heatup cycle; (3) reduced elutriation, thereby minimizing bed depth decrease during solid waste burning; (4) reduced heat losses to permit normal fluidized startup following overnight shutdowns; (5) elimination of bed clinker formation during backheating and of uncontrolled, high magnitude heat release in the combustor freeboard.

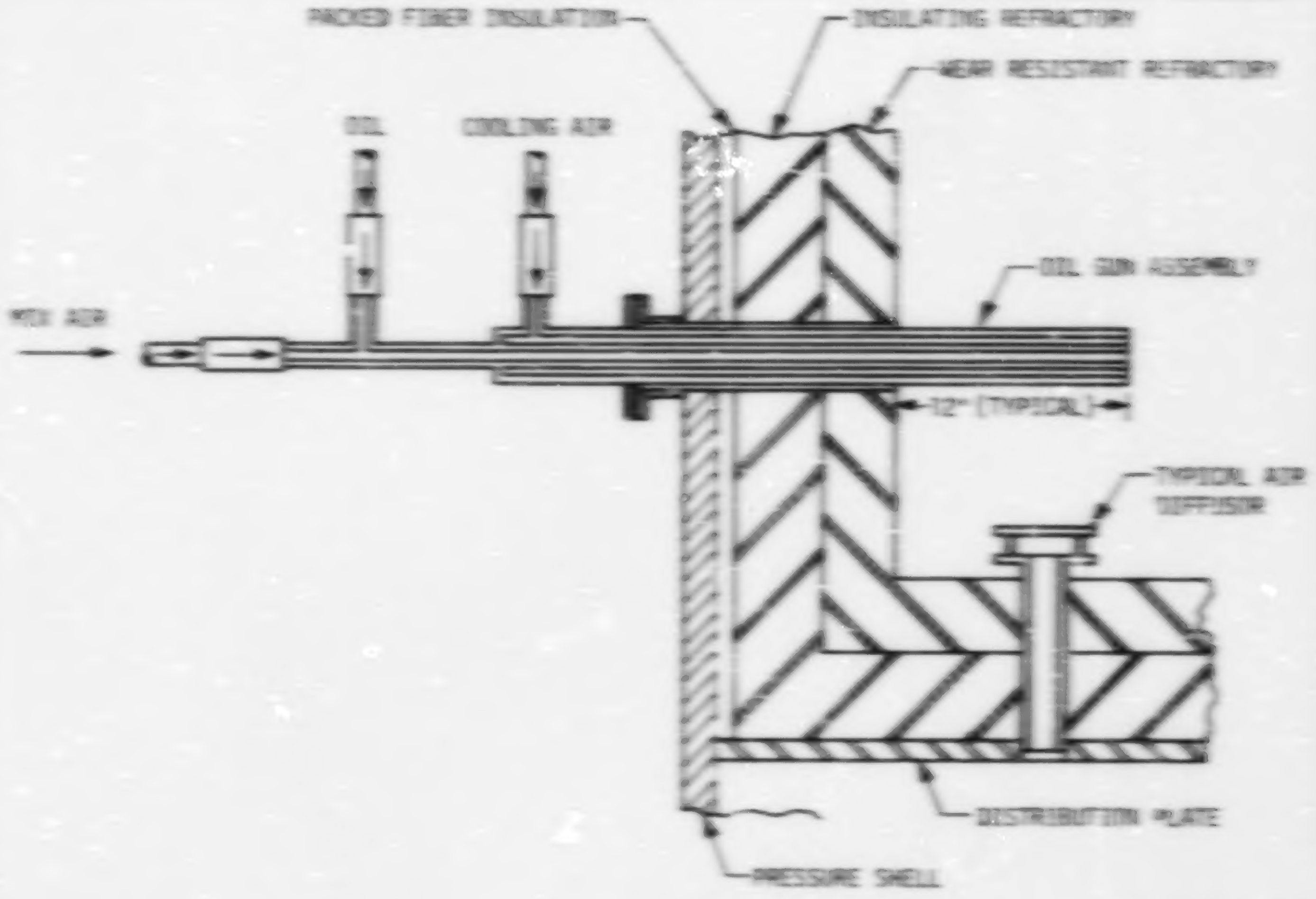

PACKED FIBER INSULATION
INSULATING REFRACTORY
WEAR RESISTANT REFRACTORY
OIL
COOLING AIR
MIX AIR
OIL GUN ASSEMBLY
12" (TYPICAL)
TYPICAL AIR DIFFUSOR
DISTRIBUTION PLATE
PRESSURE SHELL

Figure 3-12 Typical Oil Gun Assembly

Feeder Valve and Solid Waste Handling System

Processed solid waste fuel is applied to the combustor by feeder valve(s) in the Atlas storage and combustor feed subsystem. This subsystem and the shredder/air classifier/pneumatic transfer subsystem, which prepares the solid waste for combustion, comprise the solid waste handling system and were developed under a previous contract.

The airlock feeder valves transfer the solid waste from the ambient pressure zone of the Atlas storage and combustor feed subsystem conveyors to the pressurized solid waste feed piping connected to the combustor. During initial testing with the horizontal combustor, (task LP-1), a single, CPC designed, 16-inch feeder valve and a single 6-inch diameter feed pipe were used for this purpose. This configuration was changed for the LP-8 testing with the vertical combustor when two 16-inch feeder valves, each of which fed separate 5-inch diameter feedlines, were used. The 16-inch feeder valves and 5-inch feed pipes were subsequently replaced with two 30-inch rotor feeder valves and two 6-inch diameter pipes for the LP-11 testing series. These changes and other changes made to the elements of the solid waste handling system in order to satisfy the discrete requirements of the LP-1, LP-8, and LP-11 tests are discussed in Section V. A complete description of the solid waste handling system is contained in Appendix A.

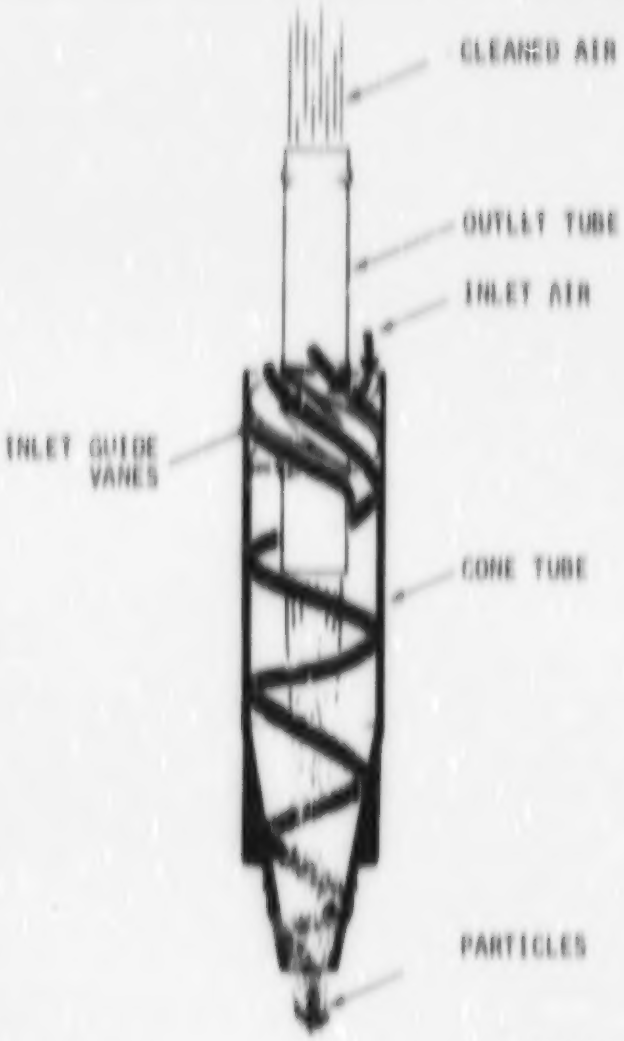
DESIGN AND DEVELOPMENT OF PARTICLE COLLECTION EQUIPMENT

The particle collection equipment described in this section consists of three full-scale separator stages, designed and tested to determine their capability to clean the combustor exhaust gas prior to its entering the CPU-400 pilot plant turbine, and a sub-scale granular filter which was designed and evaluated as a backup cleaning device. The first stage separator, designed and tested under contract task LP-12C, was evaluated using the vertical combustor during LP-8 and LP-11 testing. The second stage separator, a multi-tube cyclone assembly containing 6-inch diameter inertial tubes, was designed under a previous contract, and was evaluated with both the horizontal and vertical combustors (contract tasks LP-1 and LP-8, respectively). The third stage separator, a multi-cyclone separator containing 3½-inch diameter inertial tubes, was designed under contract tasks LP-2 through LP-4, and was evaluated with the vertical combustor during the LP-11 testing. The granular filter, designed and tested under contract task SS-2, was evaluated using the CPC Model 3 combustor.

Multi-Cyclone Tube Modules

The full-scale inertial separator design was based on testing of inertial cyclone tube modules and separators with in-house model fluid bed combustor systems. These tests were used to define tube configurations, operating characteristics and performance at operating temperature, volumetric flow, and ambient pressure conditions.

Reverse flow cyclone tubes are used in the multi-cyclone assemblies. As shown in Figure 3-13, the dirty gas enters the inlet annular cavity


CLEANED AIR
OUTLET TUBE
INLET AIR
INLET GUIDE VANES
CONE TUBE
PARTICLES

221-03

Figure 3-13 Inertial Separator Tube

which contains eight spiral-shaped vanes. The vanes impart rotational motion to the downward flowing gas which produces a vortex and centrifuges particles to the outside wall. The particles spinning along the wall decelerate and fall through the opening in the bottom of the tube into the common collection hopper. The gas exits the cyclone tube in an upward motion through the center of the finned tube. Particle separation performance measured for the selected tubes during model testing is summarized in Figure 3-14. Typical total loading measurements with the final tube designs (from model test run 13-43) are listed in Table 3-1.

Table 3-1. PARTICLE LOADING[a]

Sample set	First stage in	Second stage in	Second stage out
1	0.12	0.067	0.021
2	-	0.16	0.047
3	0.14	0.087	0.03
4	0.23	0.11	0.036
5	0.18	0.069	0.024

[a] gr/scf

The staged cyclone efficiency operating downstream of the first stage sand separator is sufficiently high to provide turbine life in excess of 20,000 hours. Life expectancy is based on test data obtained from Australian tests[2,3] burning pulverized bituminous coal. These tests were conducted on a Ruston gas turbine, basically the same as the model procured for use in the CPU-400 pilot plant. The techniques employed

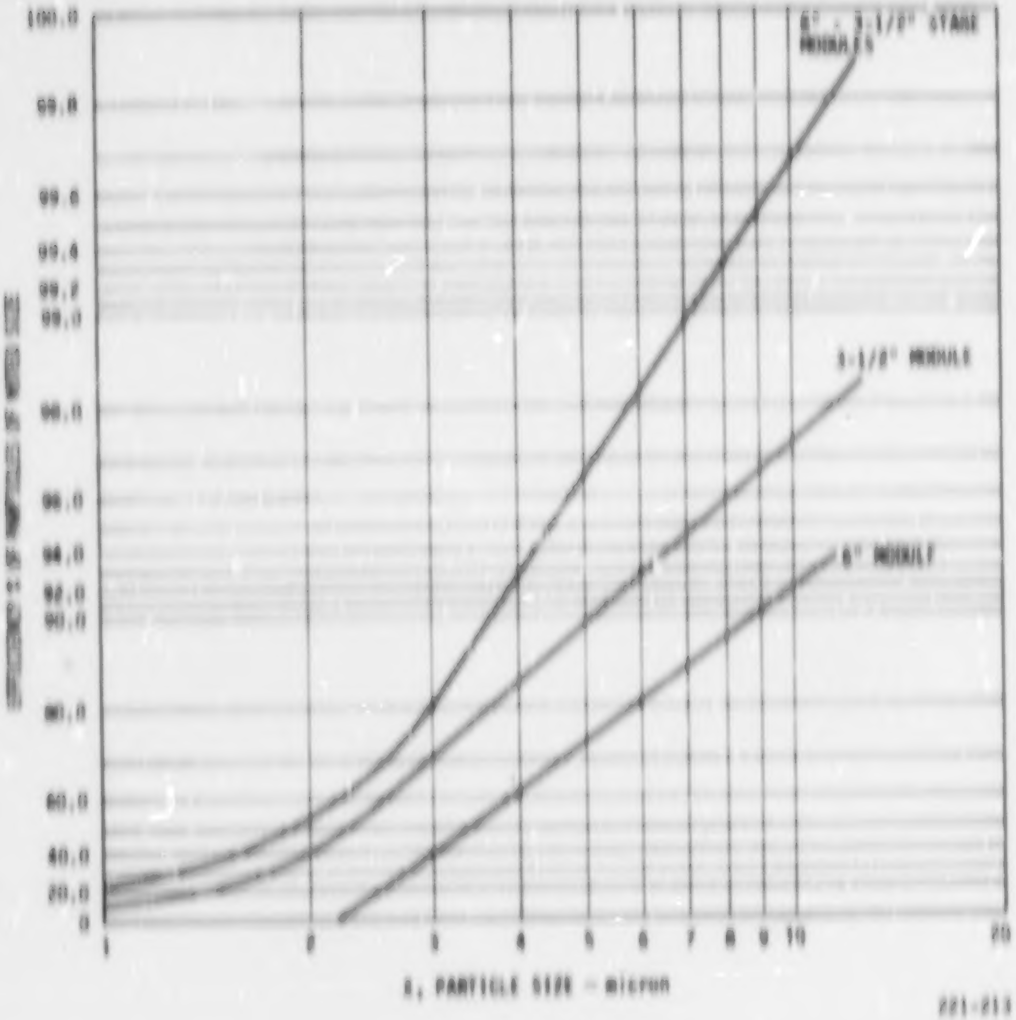


Figure 3-14 Inertial Separator Fractional Efficiency

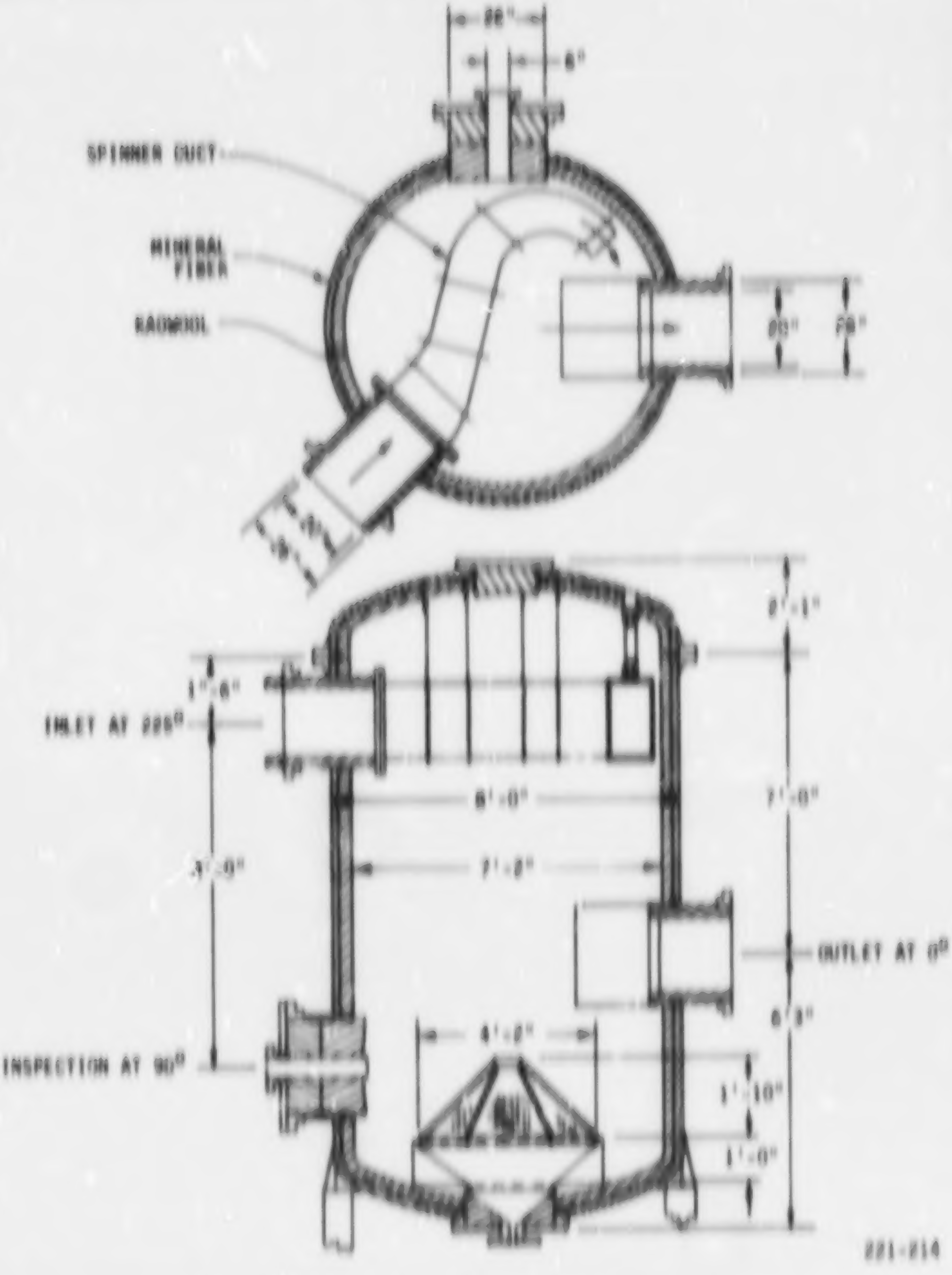
for exhaust particle sampling, particle analysis, and data reduction are described in Appendix B.

First Stage Separator (Task LP-12C)

A basic problem in the operation of a fluidized bed combustor fueled with solid waste is the elutriation of fine sand particles (particularly in the 16-100 mesh range) and the presence of molten airborne metallic particles, primarily aluminum, in the hot exhaust stream. These particles have been theorized to be small aluminum spheres protected from further oxidation by a thin, stable shell of aluminum oxide. The particles are of sufficient mass to become separated from the hot gas stream high velocity areas. Upon impact with component surfaces, the aluminum oxide shell is destroyed but is immediately reformed due to the contact of the aluminum with the oxygen-rich hot gas. With time, the continual repetition of this process results in the formation of large, hard clinker type deposits on the component surfaces.

Early inertial module tests indicated that these materials would create heavy loading, excessive wear, and material deposit and removal problems in both multicyclone separators, and that some intermediate separation device would be necessary to de-entrain the larger particles. To this end the first stage separator (sand separator) vessel was designed.

The sand separator vessel, shown in Figure 3-15, is a carbon steel pressure vessel, 8 feet in diameter and 15 feet 4½ inches high. It has a 3/8-inch thick carbon steel vessel wall that is insulated by 3 inches


22"
6"
SPINNER DUCT
MINERAL FIBER
KAOWOOL
20"
28"
2'-1"
1'-6"
INLET AT 225°
8'-0"
7'-0"
7'-2"
3'-0"
OUTLET AT 0°
6'-3"
4'-2"
INSPECTION AT 90°
1'-10"
1'-0"

221-214

Figure 3-15 First Stage Separator

of Kaowool and 2 inches of mineral fiber. The insulation is protected against erosion by a 3/32-inch stainless steel (310) sheet that is held in place with studs welded to the pressure shell. The upper portion of the vessel is a removable dome that can be easily lifted by a chain hoist when overhauling or repairing the vessel liner is required.

The first stage separator is connected directly to the combustor, and due to the simplicity of its design, it was not tested separately, but was installed on-line and its performance judged as an individual parameter within the total system.

Routine analysis of performance indicated that 70 percent of the total sand and flyash particulate stream was de-entrained in this separator vessel and was continually removed through a removal port located in the bottom of the vessel. A stainless steel screen cone prevented plugging of the removal port by large clinkers formed in the spinner duct through which the entering gas passed. The spinner duct successfully eliminated the formation of large clinkers at the initial gas impact point which had been previously encountered during pilot plant and model system tests with flat impact/deflection plates.

During LP-6 testing, separated material settled at the bottom of this vessel and was not removed. Post-test inspection revealed that fusion of this static material occurred. To alleviate this problem, a continuous material removal system, discussed in "Design and Development of the Residue Removal System" under task LP-5, was used to remove material from the bottom of this unit. Operation of the material removal system and the elimination of ash/sand agglomerations were successfully demonstrated during subsequent testing.

Second Stage Separator

The second stage full scale separator assembly (Figure 3-16) consists of an inertial separator tube holder with a residue collecting hopper, an insulated carbon steel pressure vessel with inlet and outlet flanges, a dished, insulated flanged head, and stainless steel liners. The inertial separator tube holder and hopper shown are fabricated from 310 stainless steel. The hot gases from the first stage separator enter the second stage separator inlet cavity to the 48 6-inch cyclone tubes (24 made of 310 SS and 24 made of 601 Inconel) through an internal circumferential passage. The entering gas then turns and flows through the spirally finned annular section of each tube. The configuration of the tubes investigated in the full scale separator are shown in Figure 3-17. Particulates are removed from the separator hopper through an opening on the bottom of the hopper cone. Tubes shown in Figure 3-17(c) were selected for CPU-400 pilot plant use.

The outlet pipe and conical tube section of each inertial are clamped into position against the bulkheads of the tube holder. Packed ceramic insulation is used to provide seals for the individual tubes. The housing of the separator tube assembly is held to the cylindrical pressure shell by stainless steel supports. These supports are designed to permit the radial differential expansion that occurs when the tube assembly temperature exceeds the wall temperature of the insulated carbon

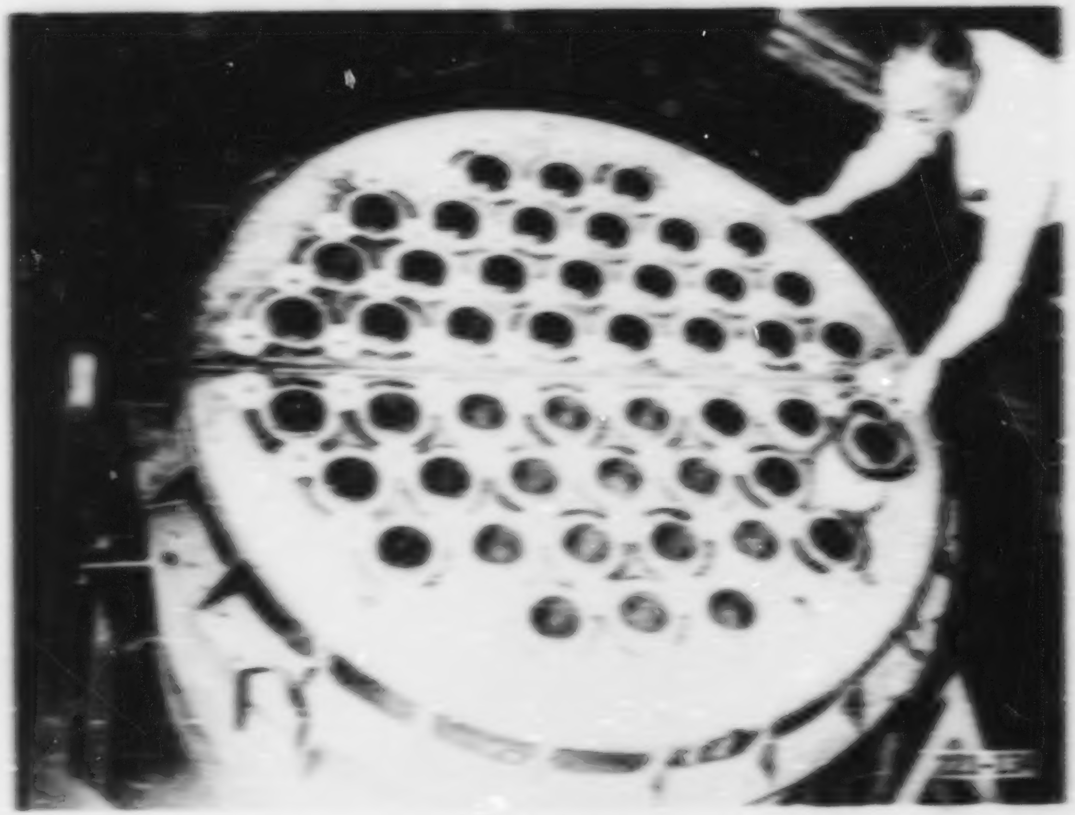


Figure 3-16 Second Stage Multicyclone Separator Tube Assembly

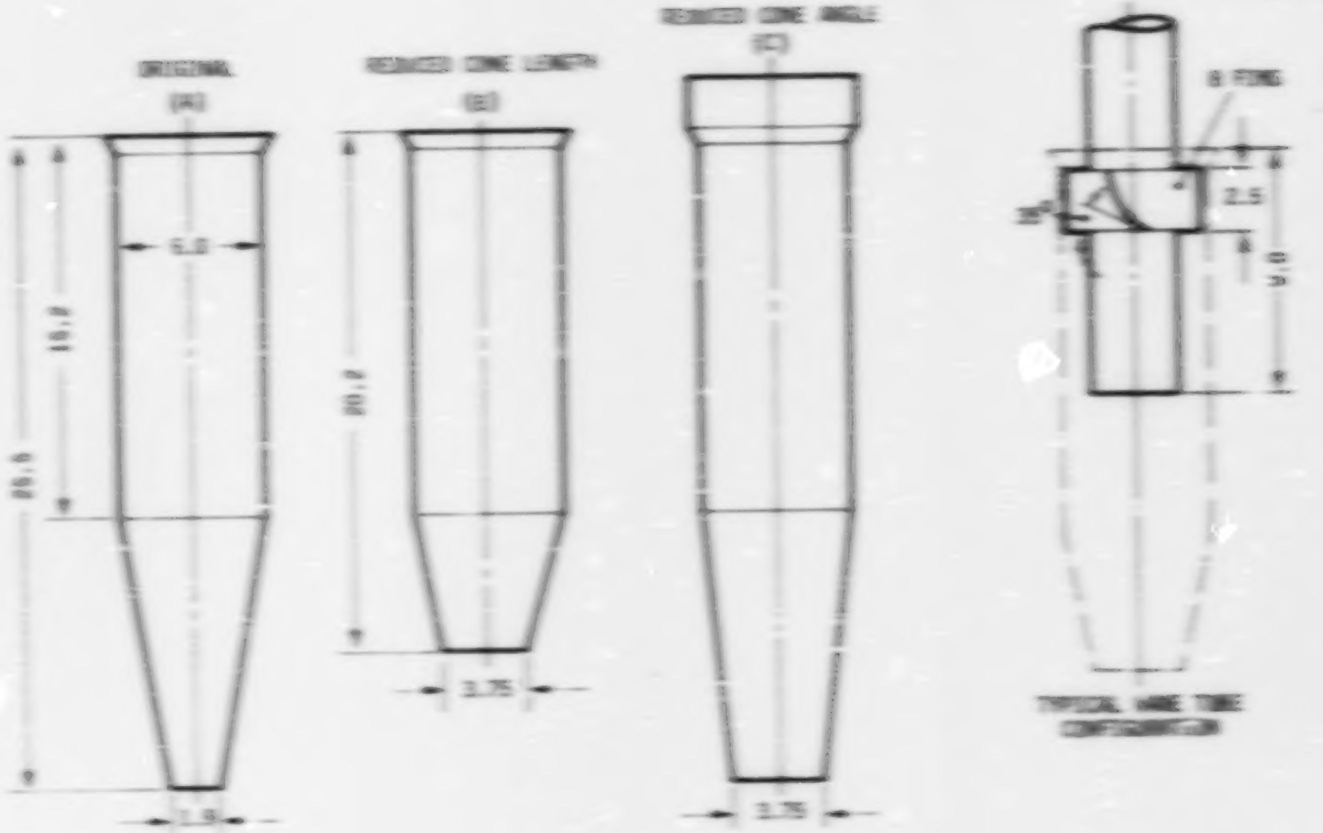

ORIGINAL
(A)
REDUCED CONE LENGTH
(B)
REDUCED CONE ANGLE
(C)
6.0
19.2
25.5
1.5
20.2
3.75
3.75
8 FINS
30°
2.5
6.0
TYPICAL VANE TUBE
CONFIGURATION

Figure 3-17 Six-Inch Diameter Tube Configurations

steel housing. This housing has an outside diameter of 8 feet and is insulated with a 4-inch thick, 8 lb/ft^3, high temperature ceramic wool blanket that is protected from erosion by a thin stainless steel liner. Stand offs are used to fasten the steel liner to the vessel wall.

As a result of the early testing, two pneumatically operated roller style vibrators were installed on the hopper cone (180 degrees apart) to prevent bridging of separated material in the cone. Bridging of materials prevents unloading of ash and produces eventual plugging of the individual tubes. The vibrator installation is shown in Figure 3-18. The vibrator is encapsulated with insulation and the air which operates the vibrator also provides for its cooling. The air exhausts from the vibrator housing assembly through a passage provided in the mounting stand-off and is mixed with the combustion gases in the plenum of the seprator assembly. The vibration is applied to the hopper skin through a 3-inch channel. The vibrator is able to provide frequencies between 8000 and 20,000 cyles per minute and forces up to 500 pounds. The piping to the vibrator is insulated with ceramic fiber rope and blanket to minimize the temperature of the air to the vibrator.

For continuous removal of separated material, the ash removal and handling system shown in Figure 3-19 was connected to the ash discharge port during all low pressure testing.

Inertial Separator Testing with the Horizontal Combustor (16-Series Tests)- These tests were performed to evaluate the operation of the inertial separator and ash removal system under conditions generated by the hot off-gases from a low pressure fluid bed combustor burning municipal

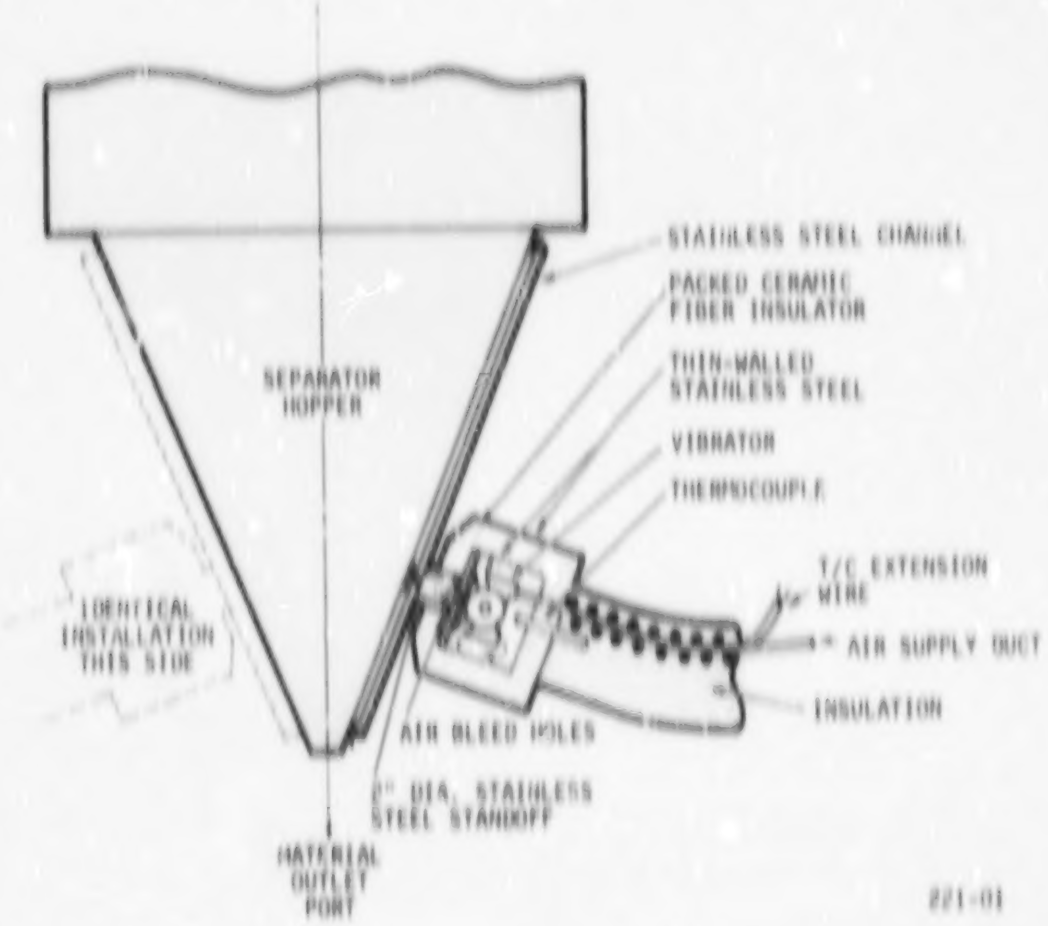

STAINLESS STEEL CHANNEL
PACKED CERAMIC FIBER INSULATOR
SEPARATOR HOPPER
THIN-WALLED STAINLESS STEEL
VIBRATOR
THERMOCOUPLE
T/C EXTENSION WIRE
IDENTICAL INSTALLATION THIS SIDE
4" AIR SUPPLY DUCT
INSULATION
AIR BLEED HOLES
2" DIA. STAINLESS STEEL STANDOFF
MATERIAL OUTLET PORT
221-01

Figure 3-18 Typical Separator Hopper Vibrator Installation

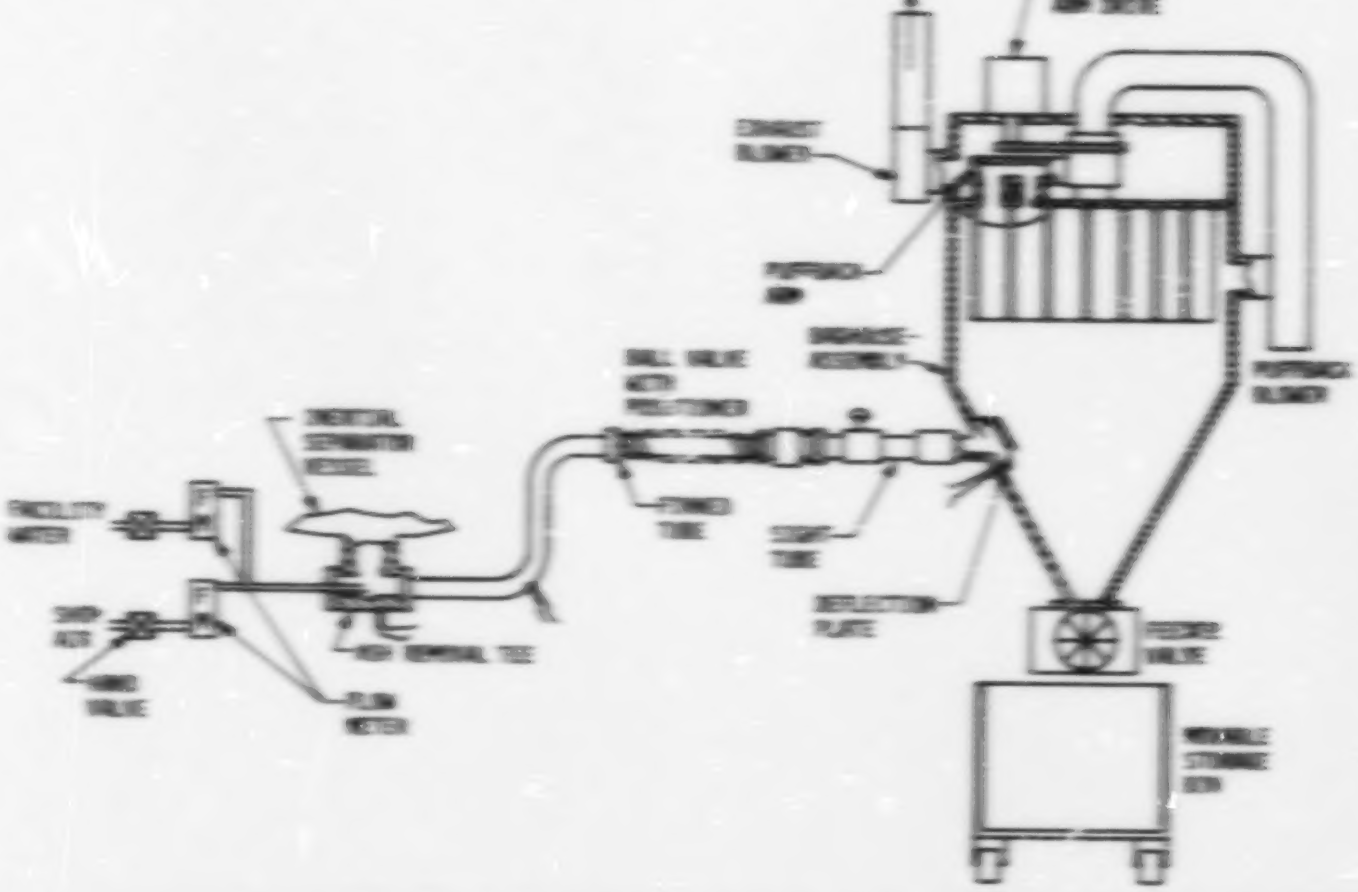

PUFFBACK AMP DRIVE
EXHAUST BLOWER
PUFFBACK AMP
BAGHOUSE ASSEMBLY
PUFFBACK BLOWER
BALL VALVE WITH POSITIONER
INERTIAL SEPARATOR VESSEL
FIXED TUBE
SOFT TUBE
DEFLECTION PLATE
FEEDER VALVE
MOVABLE STORAGE BIN
FACILITY WATER
SHOP AIR
HAND VALVE
FLOW METER
ASH REMOVAL TEE

Figure 3-19 Ash Removal and Handling System

solid waste. As seen in Figure 3-20, the separator was directly coupled to the horizontal combustor. Specifics of the tests are described in Section V.

The particles were sampled by a six-nozzle rake, downstream of the separator, with each nozzle sensing an equivalent duct area. The ratio of duct area to nozzle areas is 5000:1. For these tests, an impact wear plate was installed at the inlet impact surface of the separator housing assembly because of the high sand elutriation that existed during fluidized operation in the horizontal combustor system.

The results of the tests are summarized in Table 3-2. Plugging of individual cones were observed at the end of all runs. These plugs primarily resulted from the excessively high temperature encountered in the separator and from the inability to remove material from the common collecting hopper. The high elutriation rates from the combustor and aluminum deposits on the individual tubes dictated the necessity of the hot gas system redesign to the present configuration. Particulate data did indicate the capability of the separator to remove flyash. Also, higher velocities and larger ash outlets were beneficial in avoiding plugging. The ash removal system was capable of handling all materials coming from the separator ash outlet during all tests.

Testing with the Vertical Combustor (18-Series Tests).-

The final pilot plant system containing the vertical combustor, first stage sand separator, and second stage multi-element, reverse flow cyclone tube separator is shown schematically in Figure 3-21. The tubes

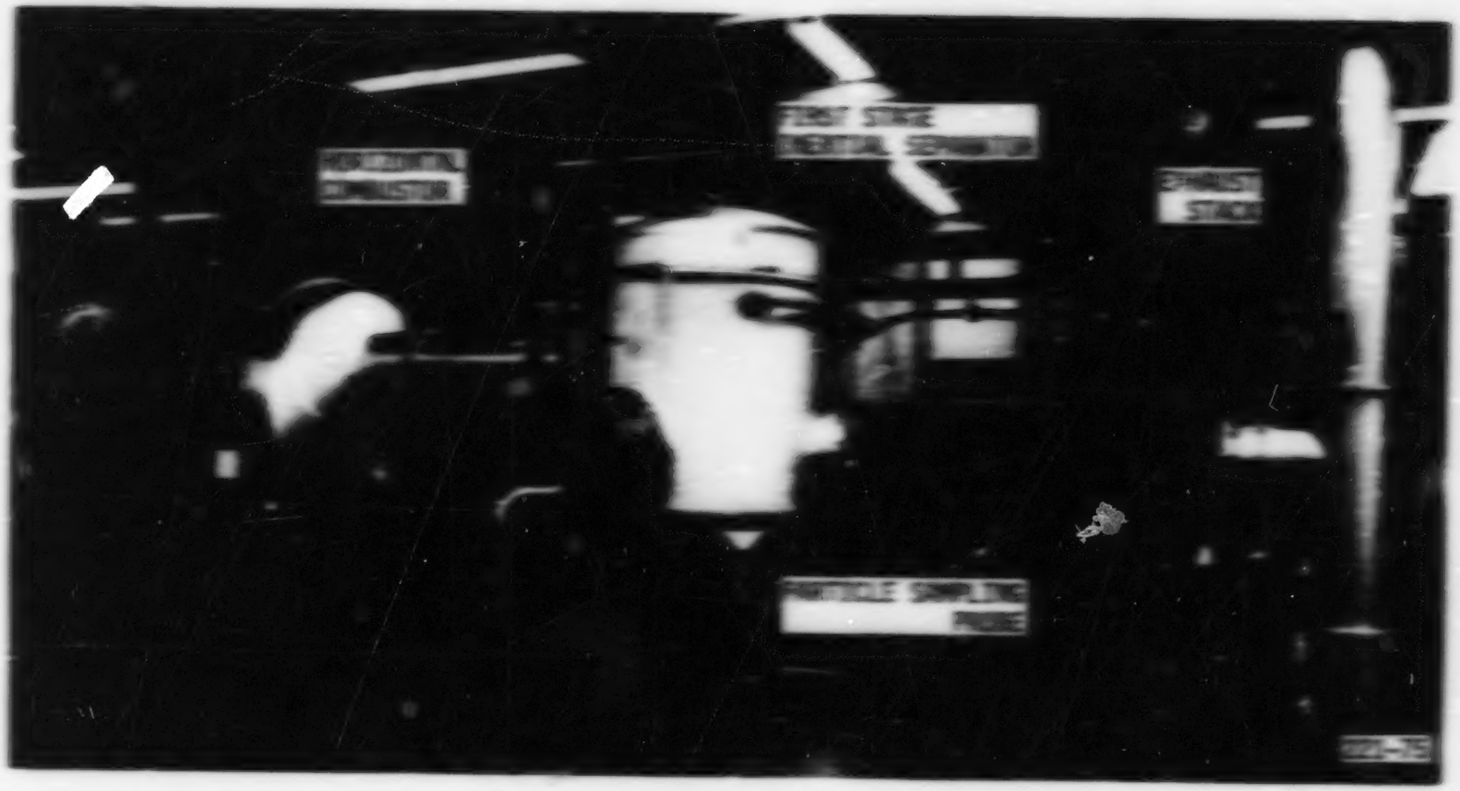

HORIZONTAL
COMBUSTOR
FIRST STAGE
INERTIAL SEPARATOR
EXHAUST
STACK
PARTICLE SAMPLING
PROBE

Figure 3-20 Separator Assembly Installed in Horizontal Combustor System

Table 3-2. 16-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Inlet flow (acfm)	Inlet temp. (°F)	Fluidized operating time (min)	Material collected (lbs)	Outlet particle loading (gr/scf)	Comments
16-1^{A-C}	13,600 (285/tube)	1580 nom. 1820 max.	174	1700 from baghouse	Not sampled	Exhaust appeared clean.
16-2^{A-C}	13,600 (285/tube)	1575 nom. 1780 max.	306	3800 from baghouse	Sample #1: 0.12 #2: 0.08 #3: 0.10 #4: 0.28	Exhaust appeared clean. Particle loading indicated tube plugging toward end of test run.
16-3^{A-C}	15,800 (340/tube)	1550 nom. 1840 max.	175	2830 from baghouse 1300 from inertial hopper	Not sampled	Cones of 15 tubes plugged. Cones of 6 tubes partially plugged. Some of the plugs in the cone ends were hard agglomerated ash deposits. Collecting hopper was full up to within 5 in. of tube ends. Partial plugs appeared to be eroding.
16-4^{A-C}	13,600 (285/tube)	1550 nom. 1750 max.	292	-	0.08	Cones of 5 tubes were entirely plugged, partial plugs in cone tubes of 31 cyclones. Many of these partial plugs appeared to be eroding. Partial plugs were hard, light brown ash agglomerations.

Table 3-2 (continued). 16-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

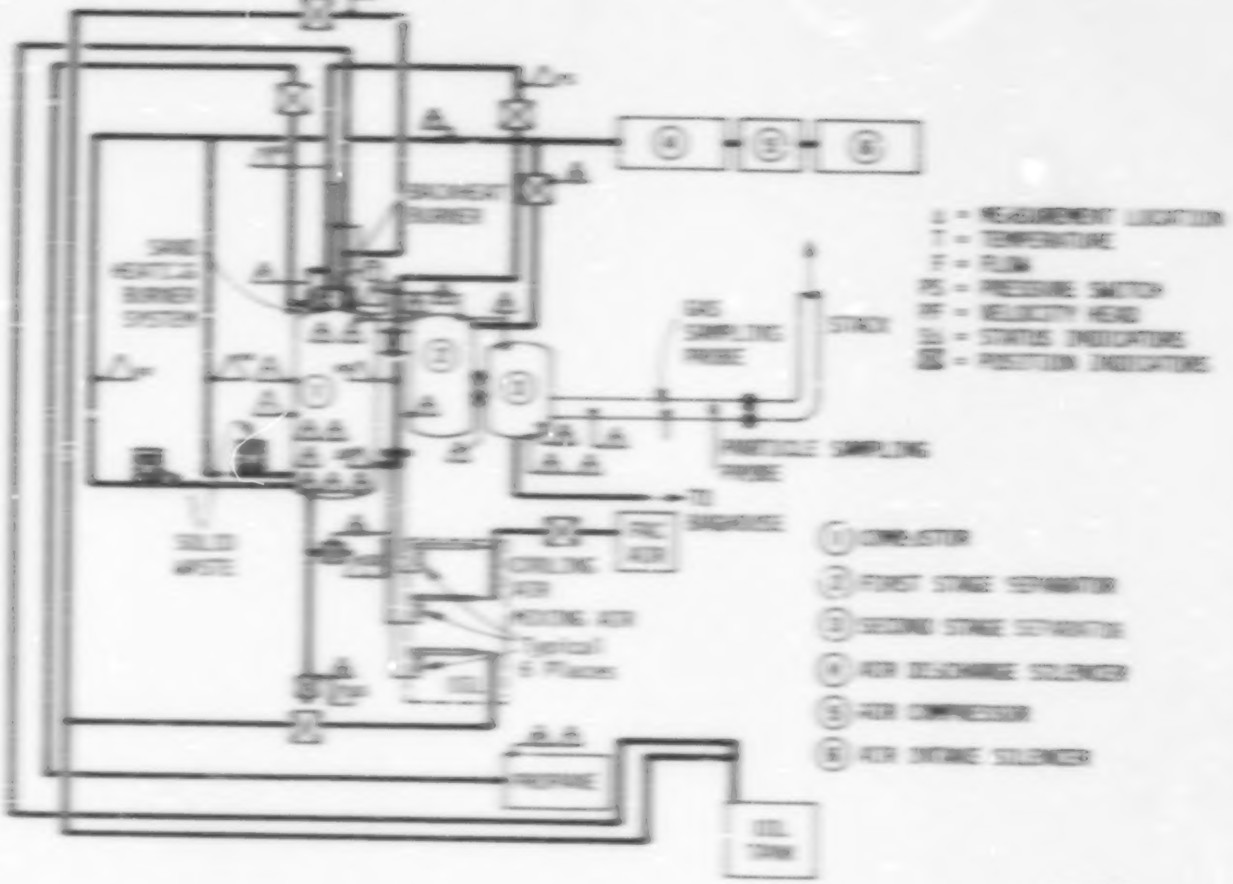
Test No.	Inlet flow (acfm)	Inlet temp. (°F)	Fluidized operating time (min)	Material collected (lbs)	Outlet particle loading (gr/scf)	Comments
16-5[b,c]	13,600 (378/tube)	1500 to 1650	30	-	Not sampled	Post-test inspection showed that cones of 2 cyclone tubes were plugged and 5 were partially plugged. Test was aborted because of combustor problems.
16-6[b,d]	13,600 (378/tube)	1500 nom. 1750 max.	133	-	Not sampled	3 cones were partially plugged.

[a] 48 active tubes were used in tests 16-1 through 16-4.

[b] 36 active tubes were used in tests 16-5 and 16-6.

[c] See detail (a), Figure 3-17, for tube configuration used in tests 16-1 through 16-5.

[d] See detail (b), Figure 3-17, for tube configuration used in test 16-6.


SAND HEATING BURNER SYSTEM
BACKHEAT BURNER
GAS SAMPLING PROBE
STACK
PARTICLE SAMPLING PROBE
TO BAGHOUSE
FAC AIR
COOLING AIR
MIXING AIR
Typical 6 Places
SOLID WASTE
PROPANE
OIL TANK
Δ = MEASUREMENT LOCATION
T = TEMPERATURE
F = FLOW
PS = PRESSURE SWITCH
VH = VELOCITY HEAD
SI = STATUS INDICATIONS
PI = POSITION INDICATIONS
① COMBUSTOR
② FIRST STAGE SEPARATOR
③ SECOND STAGE SEPARATOR
④ AIR DISCHARGE SILENCER
⑤ AIR COMPRESSOR
⑥ AIR INTAKE SILENCER

331-47

Figure 3-21 Test Setup Schematic for 10-Series Tests

in the separator assembly were modified to the (c) configuration shown in Figure 3-17. Only 24 active cyclone tubes were utilized; their arrangement is shown in Figure 3-22. The outlets of the non-active tubes were removed to provide better flow manifolding to the active tubes. The resulting holes in the outlet bulkhead were plugged with special sealing adaptors. A baffle plate was welded on top of the torroidal manifold at the inlet area to avoid possible high flow and high particle loading in tubes adjacent to the inlet connection.

The 18-series tests were utilized to meet the requirements of the 24-hour duration process controllability test of Task LP-8. Seven tests were conducted in this series. Test particulars and results are summarized in Table 3-3.

Exhaust particulate size distribution measurement data taken during runs 18-1, 18-2, 18-6, and the first sample of run 18-7 (prior to tube plugging) are shown in Figures 3-23 through 3-26. In addition to the standard sieve analysis for the flyash in the ash bin, a Coulter counter particle distribution analysis was done on ash collected in Tests 18-3 and 18-6. These data are summarized in Figures 3-27 and 3-28. Sieve analysis results for the above two samples are shown in Table 3-4.

The testing analysis indicated that although longer trouble-free operation of the separator was attained, the collecting hopper unloading and individual cyclone tube ash outlet plugging problem still existed. As a result, design modifications directed toward positive emptying of the collecting hopper were instigated in order to establish whether the

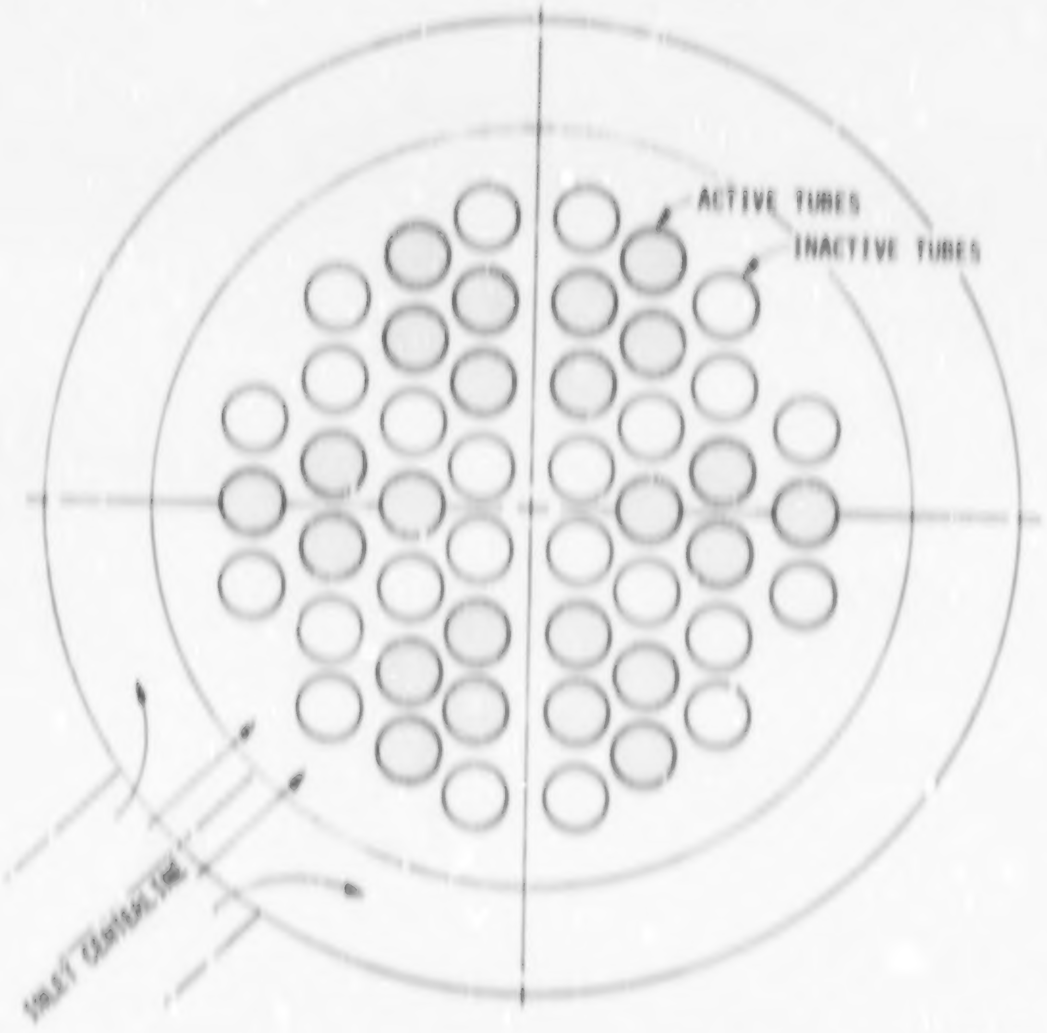

ACTIVE TUBES
INACTIVE TUBES
INLET CENTERLINE
221-48

Figure 3-22 First Stage Inertial Separator Tube Layout for 1B-Series Tests

Table J-1. 1B-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Inlet flow (acfm)	Inlet temp. (°F)	Fluidized operating time (min)	Material collected (lbs)	Outlet particle loading (gr/scf)	Comments
1B-1	15,200 (630/tube)	1500 min. 1815 max.	282	162 ash bin 170 inertial hopper.	Sample #1: 0.174 #2: 0.063	Tubes were clean except for minor fine flyash buildup in 2 tubes. The main collecting hopper did not unload completely. Remaining in hopper were 170 lb.
1B-2	15,100 (630/tube)	1550 min. 1700 max.	176	-	0.073	Not inspected, but the inertial assembly hopper did not entirely empty during the test. This material was removed with the existing pneumatic removal system prior to fluidized operation of 1B-3.
1B-3	15,100 (630/tube)	1550 min. 1760 max.	176	-	-	This test was run to verify gain settings on automatic control system stability.
1B-4	13,400 (559/tube)	1350 min. 1490 max.	161	-	-	This test was run to verify the controllability and automatic control system dynamics for the bed temperature control.

Table 3-2 (continued). 18-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Inlet flow (acfm)	Inlet temp. (°F)	Fluidized operating time (min)	Material collected (lbs)	Outlet particle loading (gr/scf)	Comments
18-5	13,700 (572/tube)	1350 nom. 1460 max.	152	–	–	The primary function of this test was to evaluate the solid waste feed control system.
18-6	15,400 (641/tube)	1520 nom. 1620 max.	111	963 ash bin & 35 sep. hop. These wts. are totals for runs 18-2 thru 18-6.	0.077	2 cone tubes had minor ash deposits on cone end. All tubes had thin ash deposits in cleaned gas outlet tube.
18-7	15,100 for 29 h 40 min 11,800 for 6 h 20 min	1520 nom. 1585 max.	36 hr	2224 ash bin & 703 sep. hopper.	Sample #1: 0.057 #2: 0.14 #3: 0.35 #4: 0.33 #5: 0.40 #6: 0.31 #7: 0.18 #8: 0.62	The official test time for the 24 hr test run started 12 hrs after initial fluidization. Data collected prior to this time was not processed. Particulate data was taken in 3 hr. intervals, starting at 15 hrs after initial fluidization. Post-test inspection revealed that the inertial tube assembly hopper did not unload at the rate material was received. This resulted in

Table 3-3 (continued). 10-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Inlet flow (acfm)	Inlet temp. (°F)	Fluidized operating time (min)	Material collected (lbs)	Outlet particle loading (gr/scf)	Comments
10-7 cont.						material backup into the cones of the individual tubes. A passage was formed through the center of the ash in the cone providing a passage for unloading some of the material. Backing up of material into individual tubes started to occur between the 1st and 2nd samples. 33 cone tubes were completely plugged. The ash-free appearance of their outlets indicated complete particle pass-through. 14 tubes had ash deposits in the cleaned gas outlets, but continued separating particles.

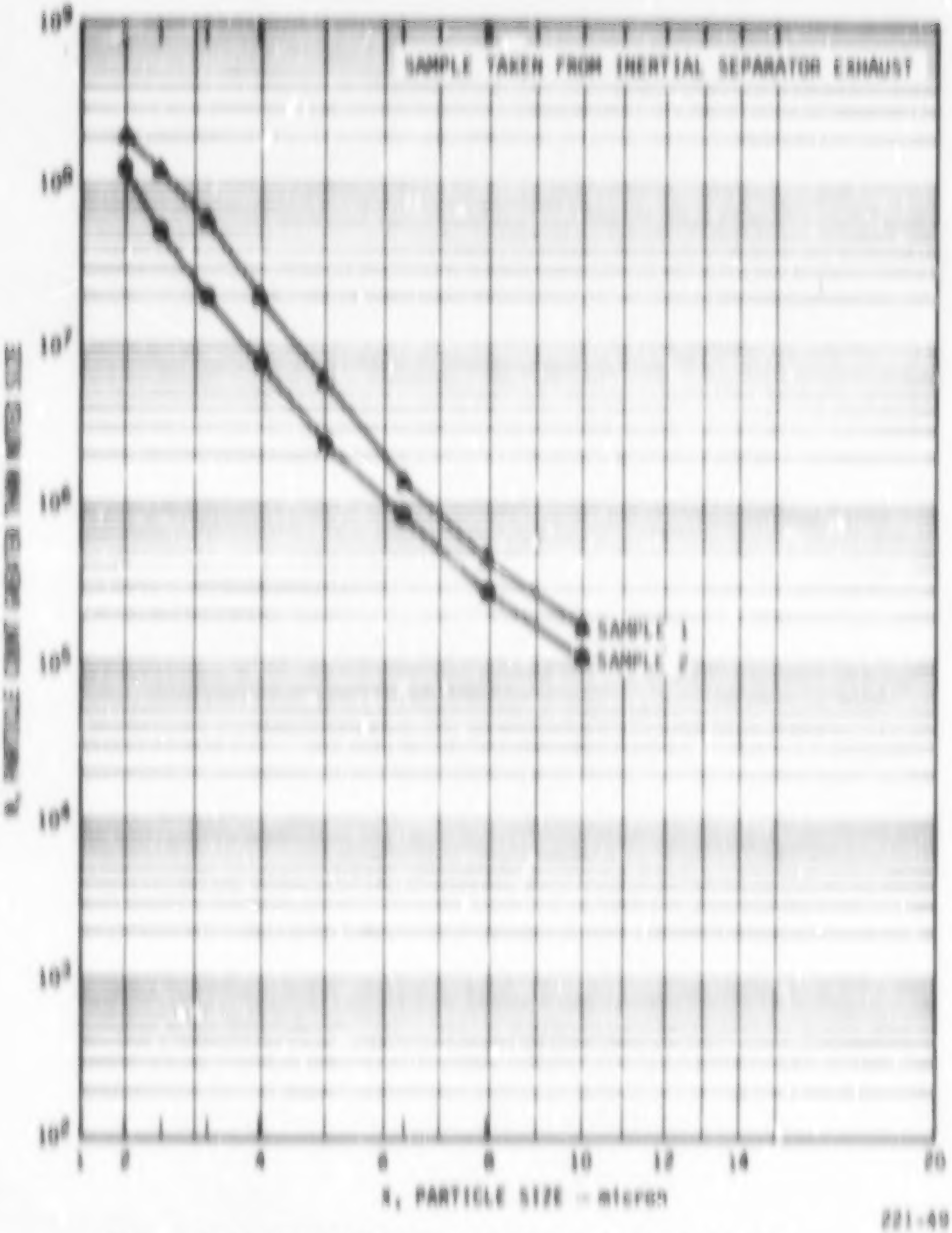


Figure 3-23 Particle Count Analysis Plot, Test 18-1

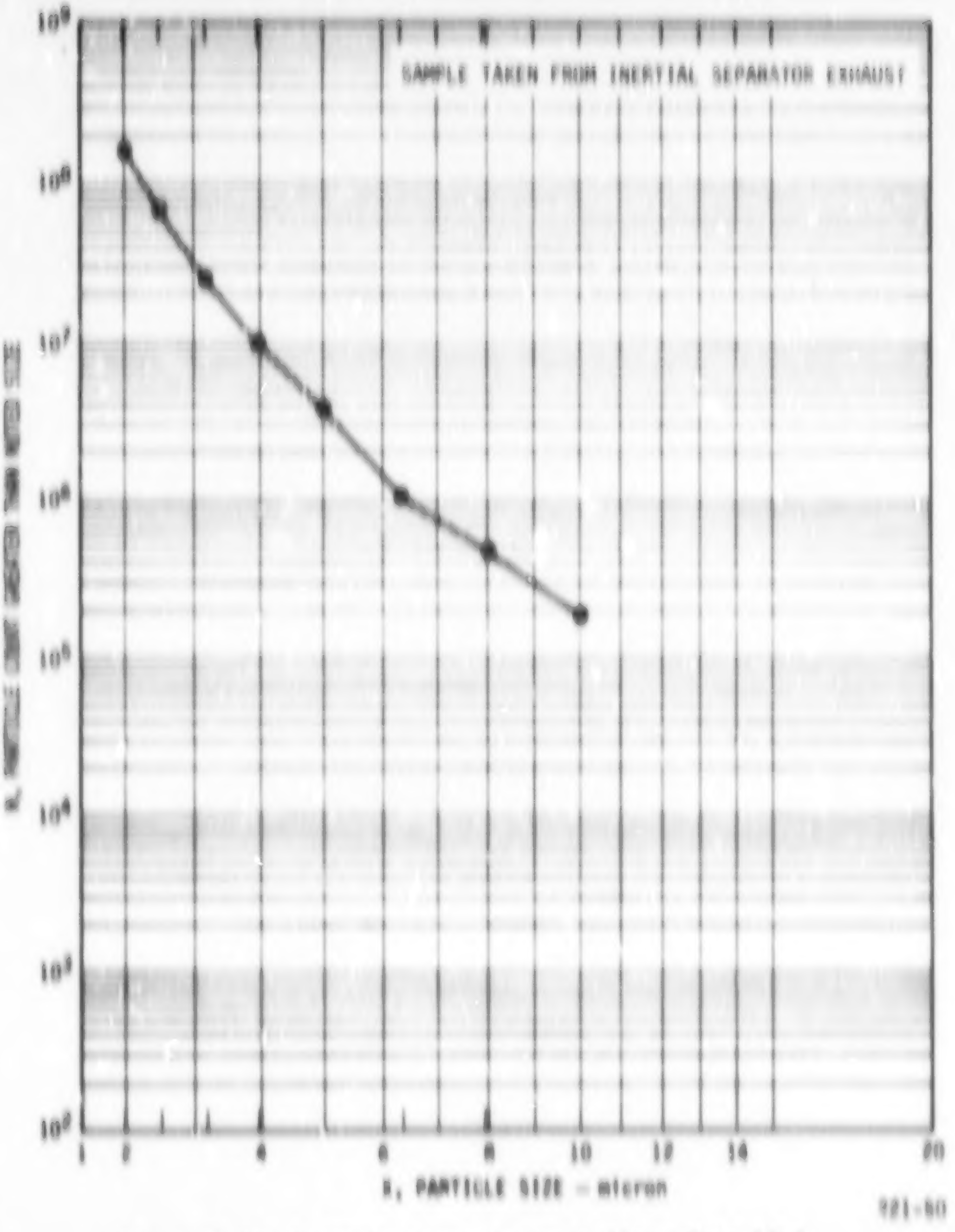


Figure 3-24 Particle Count Analysis Plot, Test 18-2

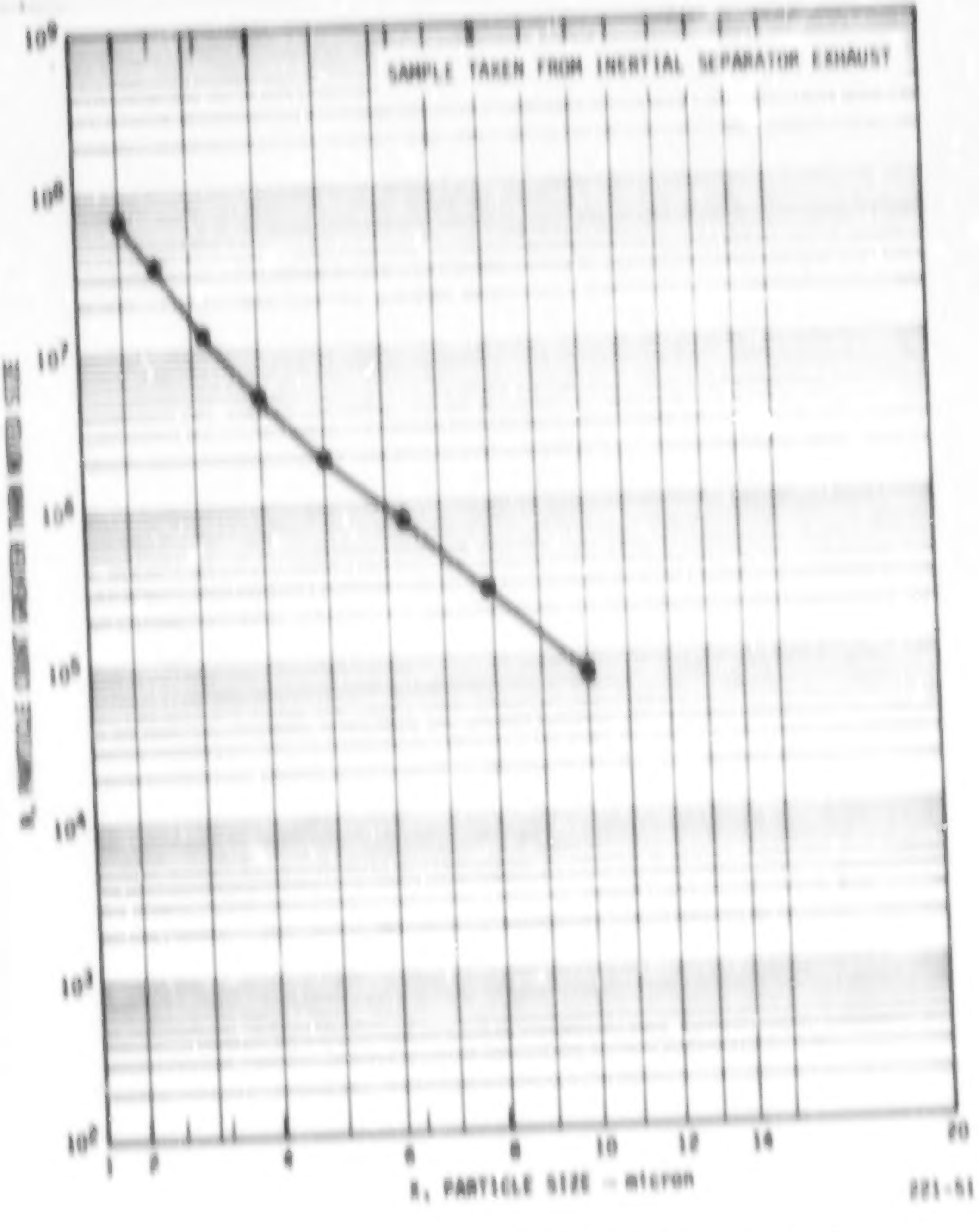
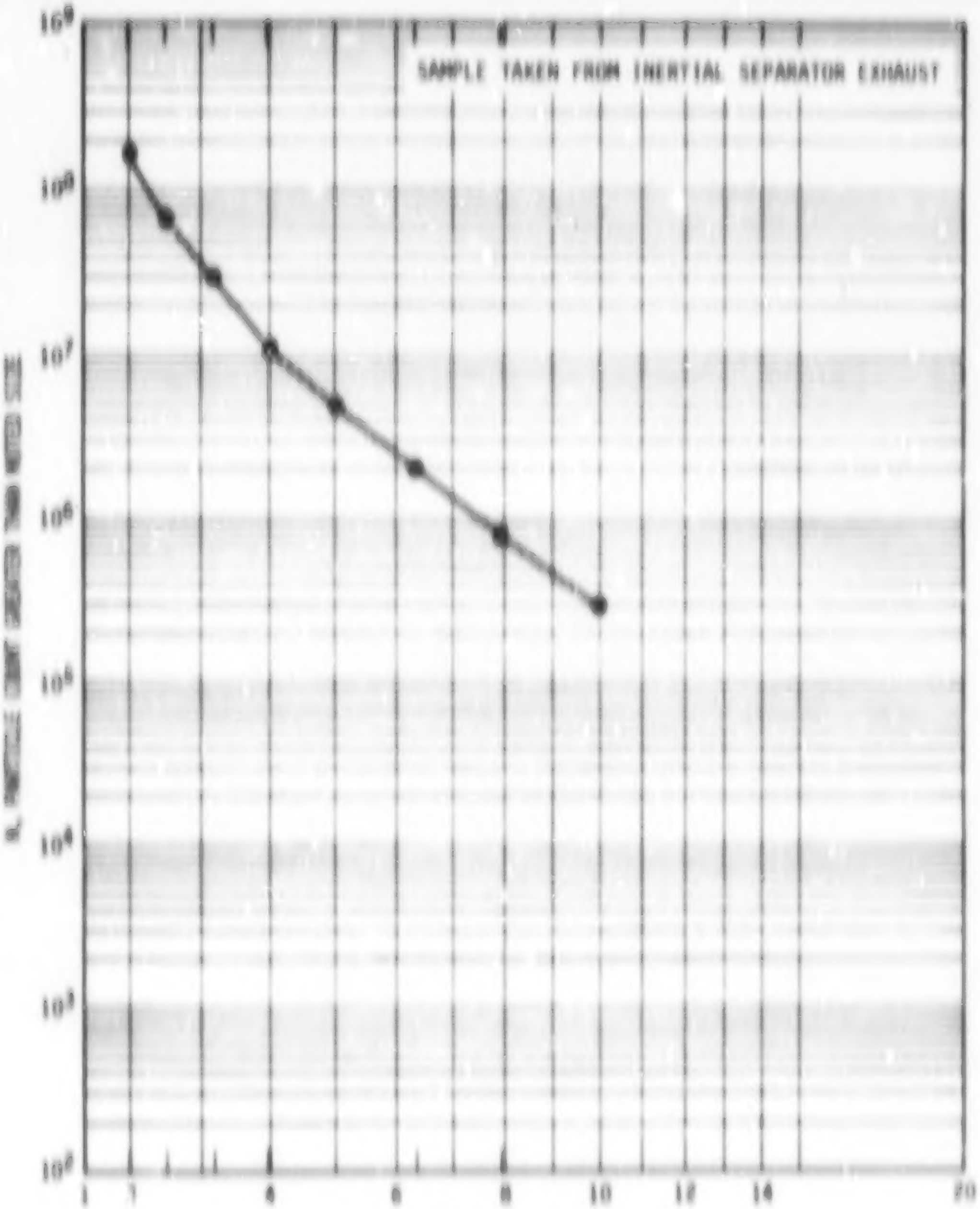
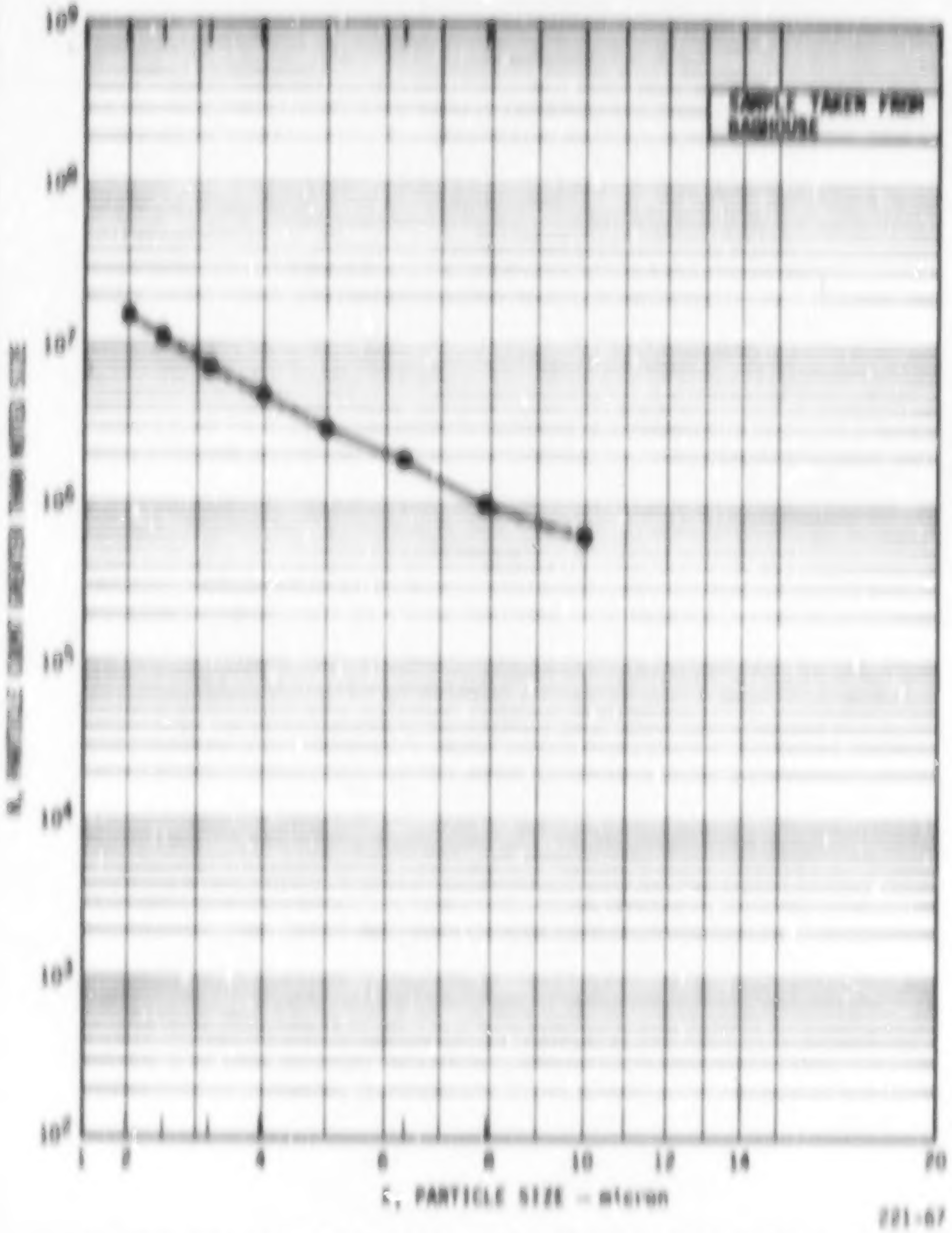


Figure 3-25 Particle Count Analysis Plot, Test 18-6



221-52

Figure 3-26 Particle Count Analysis Plot, Test 18-7 (Sample 1)



221-67

Figure 3-27 Flyash Particle Count Analysis Plot, Test 18-3

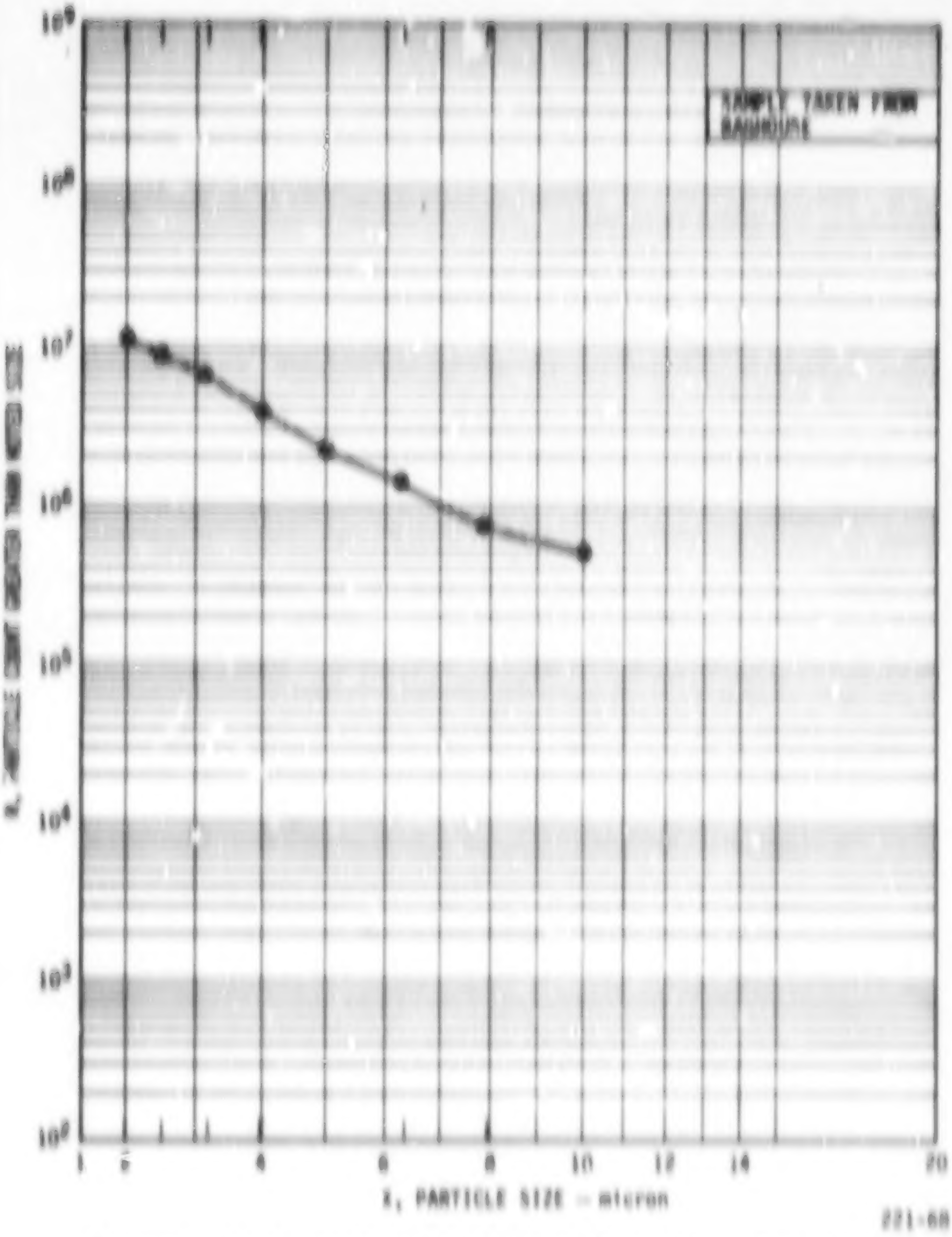


Figure 3-28 Flyash Particle Count Analysis Plot, Test 18-6

Table 3-4. SIEVE ANALYSIS DATA FOR MATERIAL COLLECTED BY THE SECOND STAGE SEPARATOR

Sieve size (U.S. Standard)	Particle size, 18-3 Sample	Percent distribution, 18-6 Sample
18	0.6	0.1
20	0.3	0.1
25	0.2	0.1
30	0.2	0.1
60	1.8	0.6
100	2.6	1.4
100+	94.3	97.6
Total sample weight	882.5 gm	406.6 gm

tube plugging resulted from separated deposits of ash in the cones of the cyclone, or if it was associated with material backup from the collecting cone into the individual cyclones.

Testing with the Vertical Combustor (20-Series Tests)-

The second stage separator was operated during the 20-series test in excess of 110 hours. During those tests, the functional operation of the assembly was to be verified. The test setup is shown schematically in Figure 3-29, and the results are summarized in Table 3-5. The tube configuration used during these tests is depicted in Figure 3-17(c). The tube arrangement is shown in Figure 3-30.

During the initial testing it was found that the ash removal line at the hopper outlet plugged and the periodic plugging of individual tube cones occurred. The ash outlet of the collecting hopper was modified after the 20-4A test resulting in successful ash unloading during subsequent tests.

After the hopper unloading problem was solved, it was found that plugging of individual tubes still occurred and thus the plugging was not entirely associated with initial backup into cones due to the hopper problem or due to absence of bleed flow. Following a series of model tests in which rattlers were used to wipe the cones continuously, chain and rod rattlers were incorporated into the full scale configuration and tested. No deposits were found in the tubes where this chain type of device was installed.

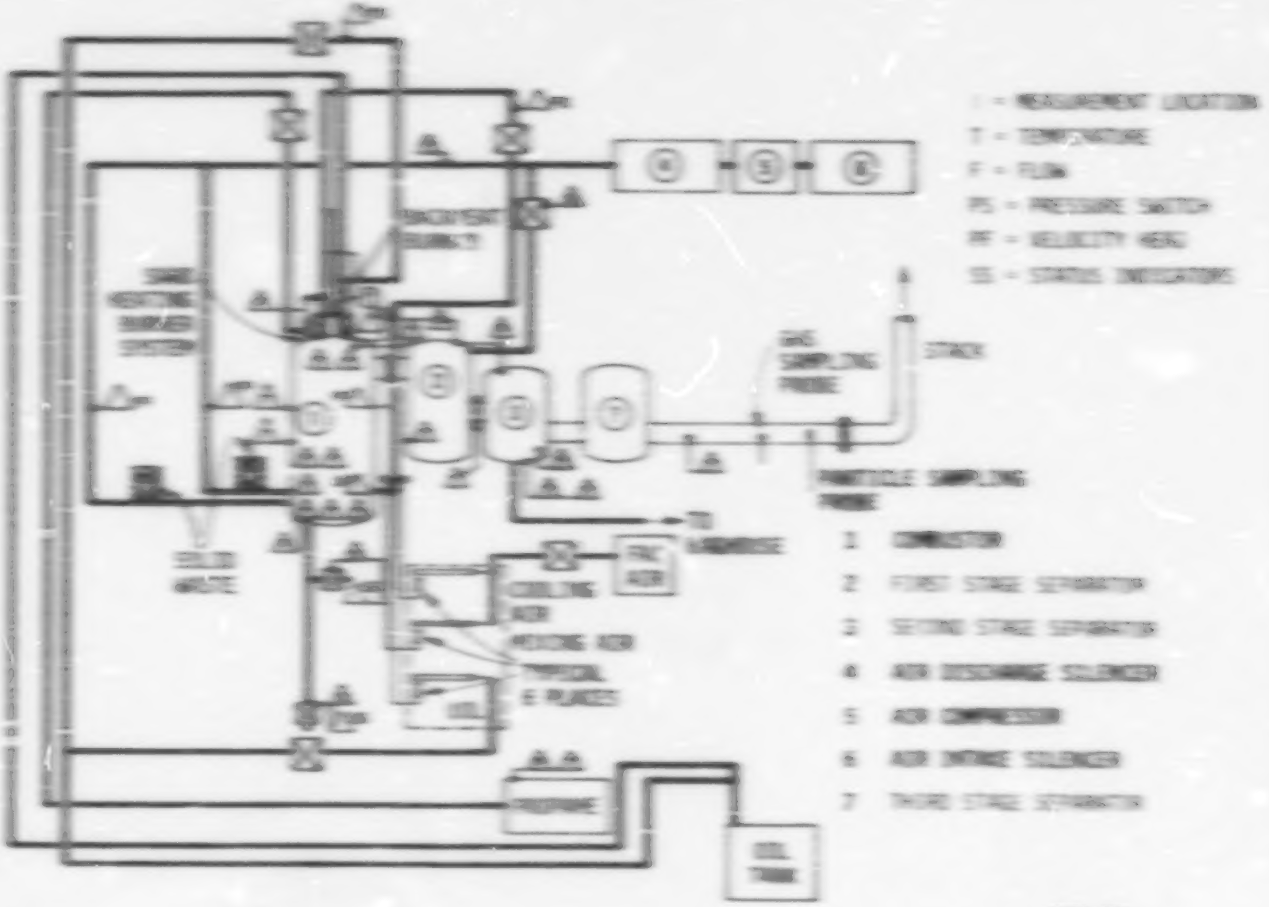

SAND HEATING BURNER SYSTEM
BACKVENT BURNER
SOLID WASTE
COOLING AIR
MIXING AIR
TYPICAL 6 PLACES
PROPANE
OIL TANK
FAC AIR
TO BAGHOUSE
GAS SAMPLING PROBE
STACK
PARTICLE SAMPLING PROBE
1
2
3
4
5
6
7
△ = MEASUREMENT LOCATION
T = TEMPERATURE
F = FLOW
PS = PRESSURE SWITCH
PF = VELOCITY HEAD
SS = STATUS INDICATORS
1 COMBUSTOR
2 FIRST STAGE SEPARATOR
3 SECOND STAGE SEPARATOR
4 AIR DISCHARGE SILENCER
5 AIR COMPRESSOR
6 AIR INTAKE SILENCER
7 THIRD STAGE SEPARATOR
221-98

Figure 3-19 Test Setup Schematic for 20-Series Tests

Table 3-5. 2D-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Nominal flowrate through assembly (lb/min)	Nominal inlet temp. (°F)	Fluidized operating time on solid waste (hrs)	Active tube pattern (Figure ref.)	Comments
2D-2A & -2B	350	1500	3	3-22	Airline connections to vibrator body failed on both vibrators. Separated ash removal system failed to maintain ash hopper clear of material. Airlines to the vibrators were redesigned and reworked to incorporate flexlines.
2D-2C	350	1490	3.5	3-22	Vibrators operated satisfactorily during the entire test. Ash removal tee was plugged and ash accumulated in the hopper. Rawwool and small ash agglomerations were found in the tee. After cleaning, the ash removal system performed satisfactorily.
2D-3	350	1486	12.2	3-22	Two of the 24 separator tube cones were plugged. The ash removal tee plugged. Tube pattern change for subsequent tests implemented.
2D-4A	350	1440	33	3-[illegible]	Ash removal from hopper was unsuccessful despite efforts to keep the tee open. Post-test inspections showed that the hopper was full (460 lb) of separated material. The level of material in the hopper was in the proximity of the individual cone outlets. All cone outlets were found to be plugged.

Table 3-5 (continued). 20-SERIES SECOND STAGE SEPARATOR TEST SUMMARY

Test No.	Nominal flowrate through assembly (lb/min)	Nominal inlet temp. (°F)	Fluidized operating time on solid waste (hrs.)	Active tube pattern (Figure ref.)	Comments
20-4B	300	1450	51.6	3-31	Prior to this test the ash outlet was modified by increasing the hopper outlet diameter to 5.6 inches and by adding a secondary collection hopper to the side of the tee. A ramrod was incorporated into the setup to push deposits into this secondary hopper. Post-test inspection showed that the hopper was free of ash and two cyclone tube outlets were plugged. The lower flowrate was obtained by overboard dump of 50 lb/min of compressor air.
20-5	350	1475	8.2	3-31	Mechanical rattlers were installed in 10 tubes. 7 were chain rattlers and 3 were rod rattlers. They were pivoted at the exhaust plane of the vane tubes. Post-test inspection showed two tubes (without rattlers) were plugged; the tubes with the rod type of rattler had ash deposits at their outlets. The open area was approximately 25 percent of its initial value.

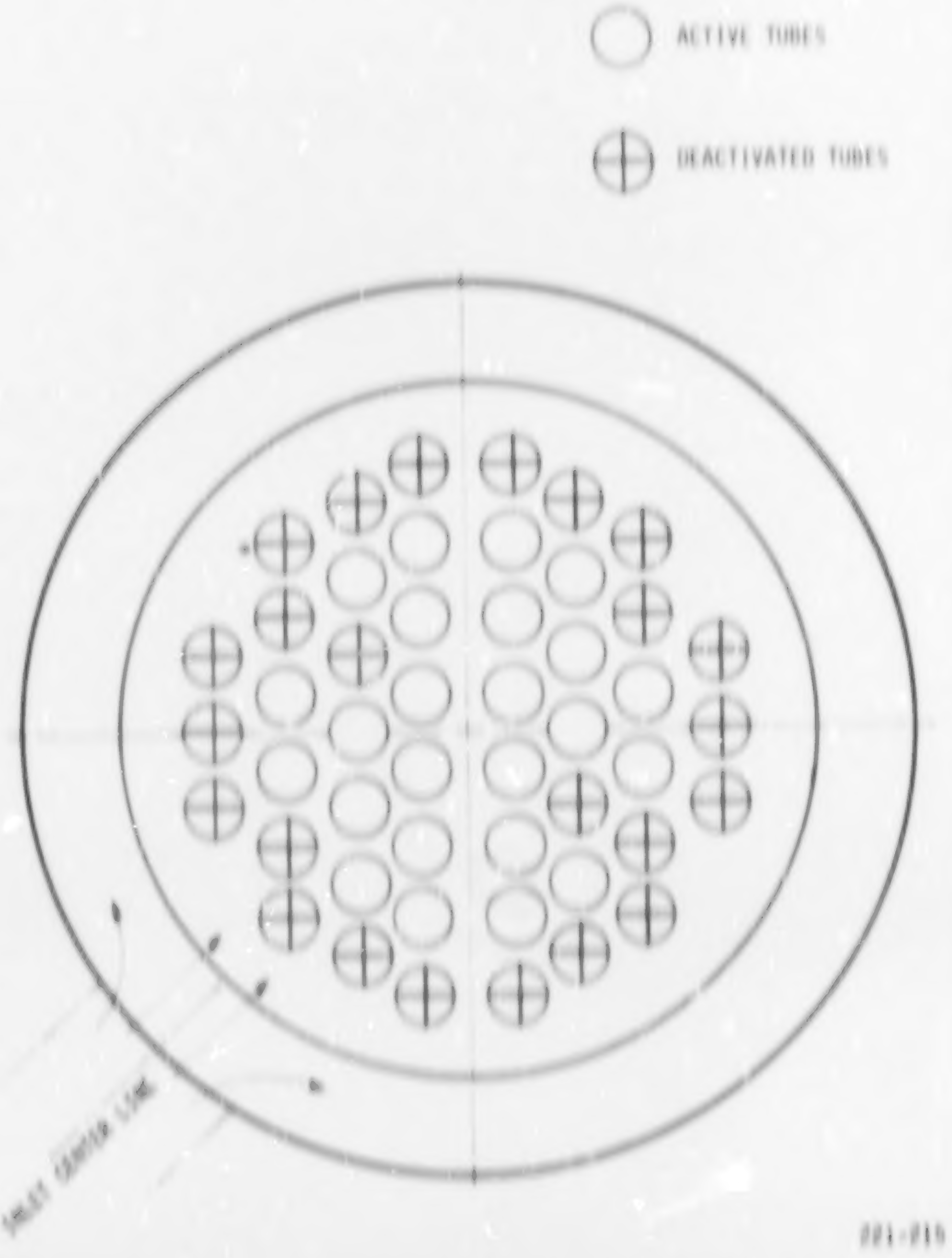

ACTIVE TUBES
DEACTIVATED TUBES
INLET CENTER LINE
221-215

Figure 3-30 Six-Inch Diameter Tube Arrangement of Second Stage Separator

At the conclusion of the 20-series tests, the 6-inch inertial separator was disassembled and inspected. The result of the inspection indicated that the seals between the dirty gas aisle and clean gas aisle performed well, with little evidence of leakage. There was a moderate buildup of aluminum on the outer diameter surface of the inertial tube exhaust piping, which is exposed to the gas as it enters from the first stage separator. Figure 3-31 shows a buildup of flyash agglomeration in the same area of the inertial separator which was precipitated by the aerodynamic stagnation areas developed in the area of the vanes. Consultation has been initiated with a view to effecting a solution for the ash buildup in the area of the vanes.

Inspection of the shingles, which make up the inner liner of the vessel, showed no sign of deterioration from either corrosion or erosion. The wall temperatures indicated that the Kaowool insulation was satisfactory in holding the vessel wall to a reasonable (130° F to 180° F) range.

Third Stage Separator

The third stage inertial separator assembly is shown in Figures 3-32 and 3-33. Its design, fabrication, and testing were performed under Tasks LP-2, LP-3, and LP-4, respectively. The separator assembly consists of a carbon steel pressure shell that is insulated by a 2-inch thick layer of mineral wool and a 3-inch layer of high temperature Kaowool. The insulation is protected from erosion by the high velocity exhaust gases by a 310 stainless steel liner that consists of two dished end closures and a cylindrical center section. The insulation is held in place by studs welded to the pressure vessel wall.

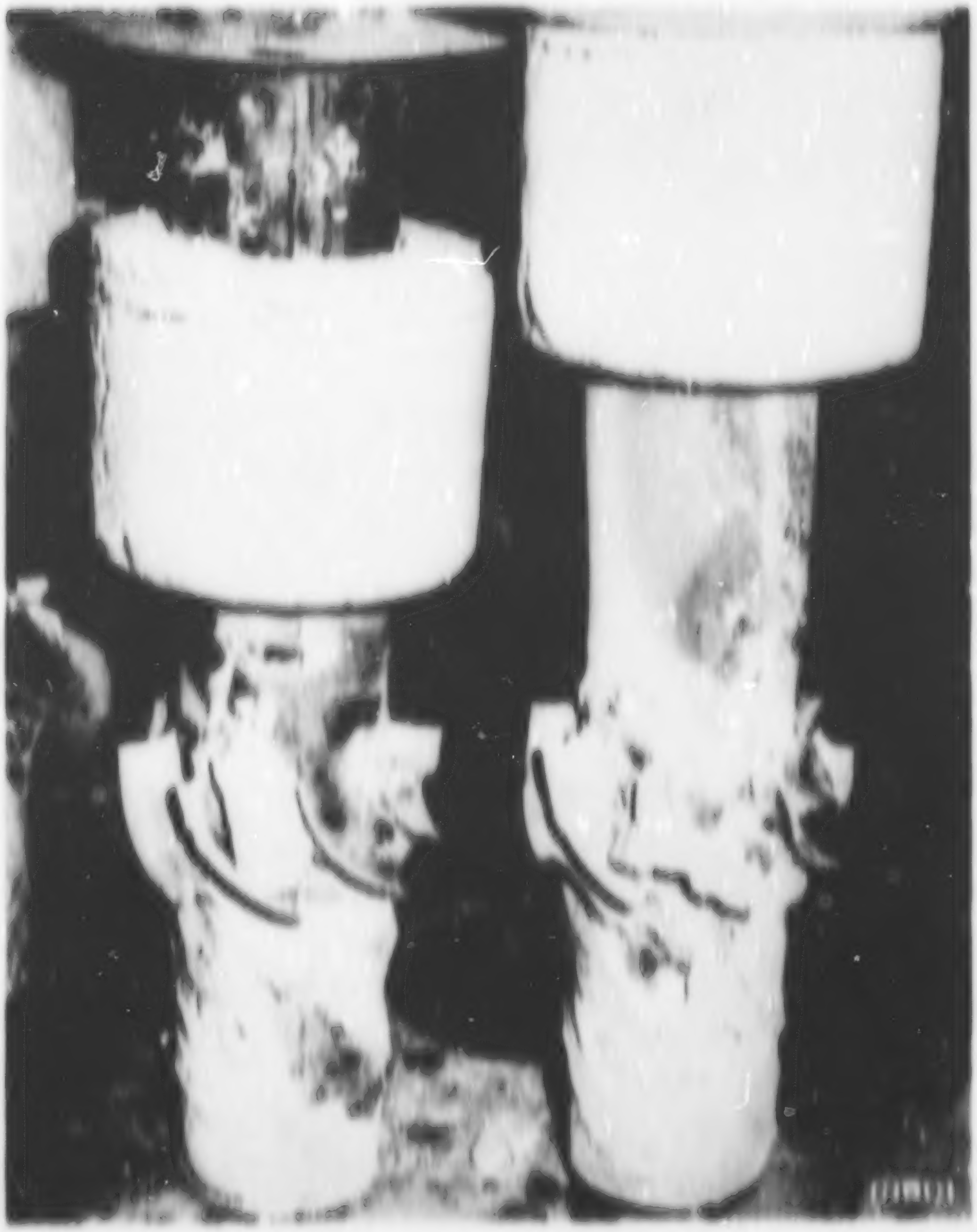
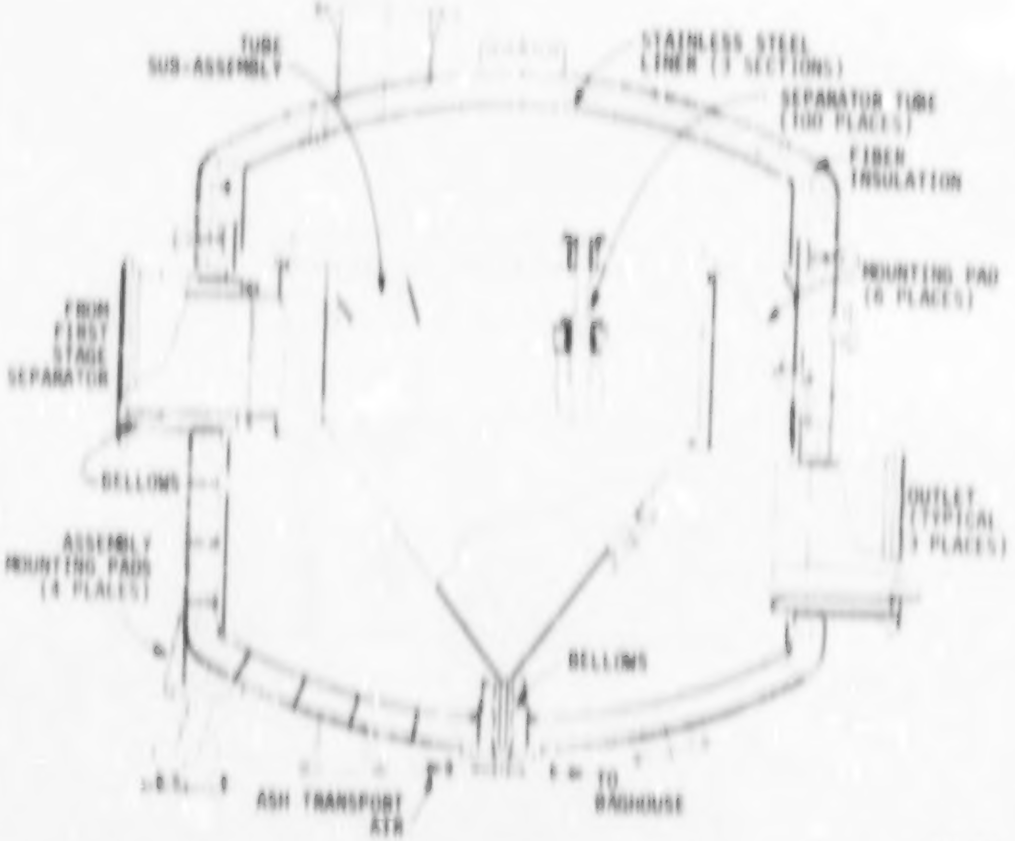


Figure 3-31 Ash Deposits in Vane Section of Second Stage Separator Tube


TUBE SUB-ASSEMBLY
STAINLESS STEEL LINER (3 SECTIONS)
SEPARATOR TUBE (100 PLACES)
FIBER INSULATION
MOUNTING PAD (6 PLACES)
FROM FIRST STAGE SEPARATOR
BELLOWS
ASSEMBLY MOUNTING PADS (4 PLACES)
OUTLET (TYPICAL 3 PLACES)
BELLOWS
ASH TRANSPORT AIR
TO BAGHOUSE

221-02

Figure 3-32 Third Stage Inertial Separator Assembly

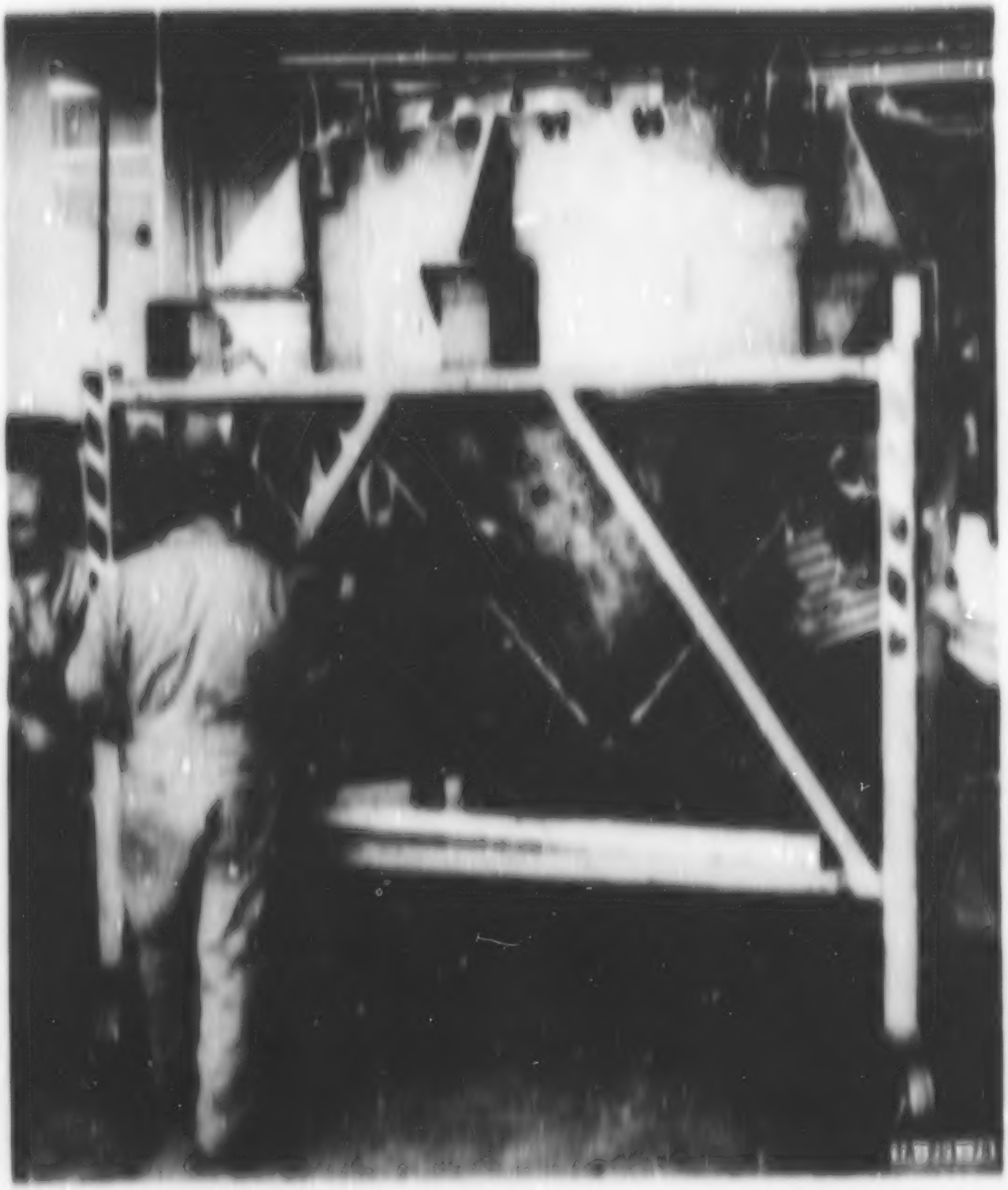


Figure 3-33 Third Stage Cyclone Tube Assembly

A bellows assembly was used in the dirty gas inlet port liner to prevent leakage of particles past the inertial tube assembly and to provide the flexibility necessary to absorb the differential expansion associated with the heating and cooling of the inner components. Two of the three 26-inch diameter flanges in the lower cylindrical section provided gas exhaust into the overboard stack during low pressure operation and into the compressor turbine during high pressure operation. The third flange provides a hot gas inlet from the turbine combustor. During operation, the ports not required are blanked off.

The inner surface of the carbon steel pressure shell is protected from corrosive acid attack due to water condensation in the exhaust gas environment with a coating of bisonite phenoflex, the identical coating system used in the vertical combustor and first stage separator. The outer surface of the vessel is coated with high temperature paint.

The inertial separator tube subassembly contains 100 2½-inch diameter, 310 SS tubes whose design is based on the testing of a three-tube module. The tubes are arranged in 20 sets of four-tube modules which form radial rows around the outer periphery. Mounted in the inner surface are four three-tube modules and four two-tube modules. Fiberfrax rope packings seal the cone assemblies and outlet tube assemblies in their respective bulkheads. The outer housing of the assembly and the inner housing containing the tubes are eccentric and this forms an annular passage that provides good flow distribution by minimizing velocity variations around the periphery. Six mounting pads are provided between the pressure vessel and tube housing assembly to reduce local loading and stress concentrations in the thin section tube housing.

The cones of the inertial tubes discharge the separated particles into a common collecting hopper from which the material is pneumatically transported into the baghouse assembly through a 1-inch diameter pipe. The cyclone tube configuration is defined in Figure 3-34. As on the second stage separator hopper, two vibrators are installed on the unloading cone to prevent material bridging.

Cold Flow Testing

Cold flow tests were conducted by the Donaldson Company in Minneapolis, Minnesota with the setup shown schematically in Figure 3-35 and pictorially in Figure 3-36. The air flow resistances across the inertial inlet and the separator assembly are shown in Figure 3-37. Flow distribution measurements were made by measuring the air flow rate (velocity head) exiting through each cyclone tube. These results are summarized in Figure 3-38.

During the particle collection efficiency tests, the air flow was set and maintained at 15,000 cfm. Standard AC fine test dust was injected into the unit at a rate of 0.025 gm/ft^3 of air flow (375 gm/min) through a 30-gallon barrel dust feeder. A total of 98 pounds of dust was fed in a 2 hour period. The test data is cited in Table 3-6.

Upon completion of the test, a weight balance was performed by weighing the amount of dust fed (44,492 gm), dust on the absolute filter (8093 gm),

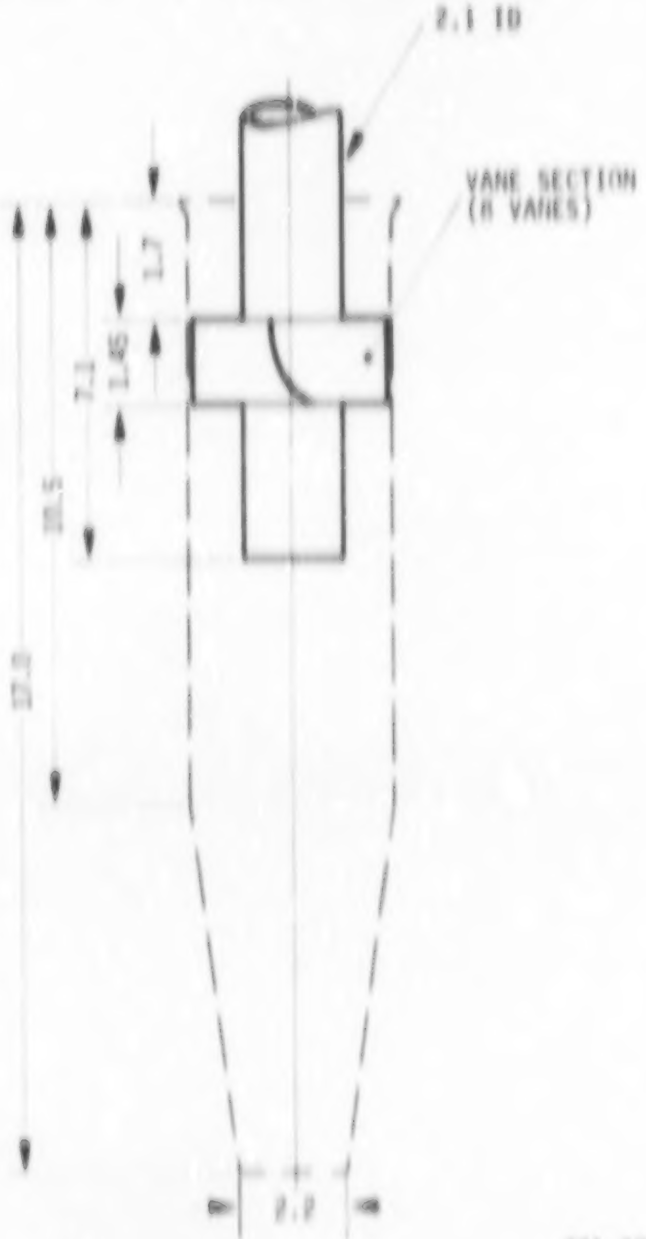

2.1 ID
VANE SECTION
(8 VANES)
1.7
1.45
7.1
10.5
17.0
2.2
221-08

Figure 3-34 Third Stage Cyclone Tube

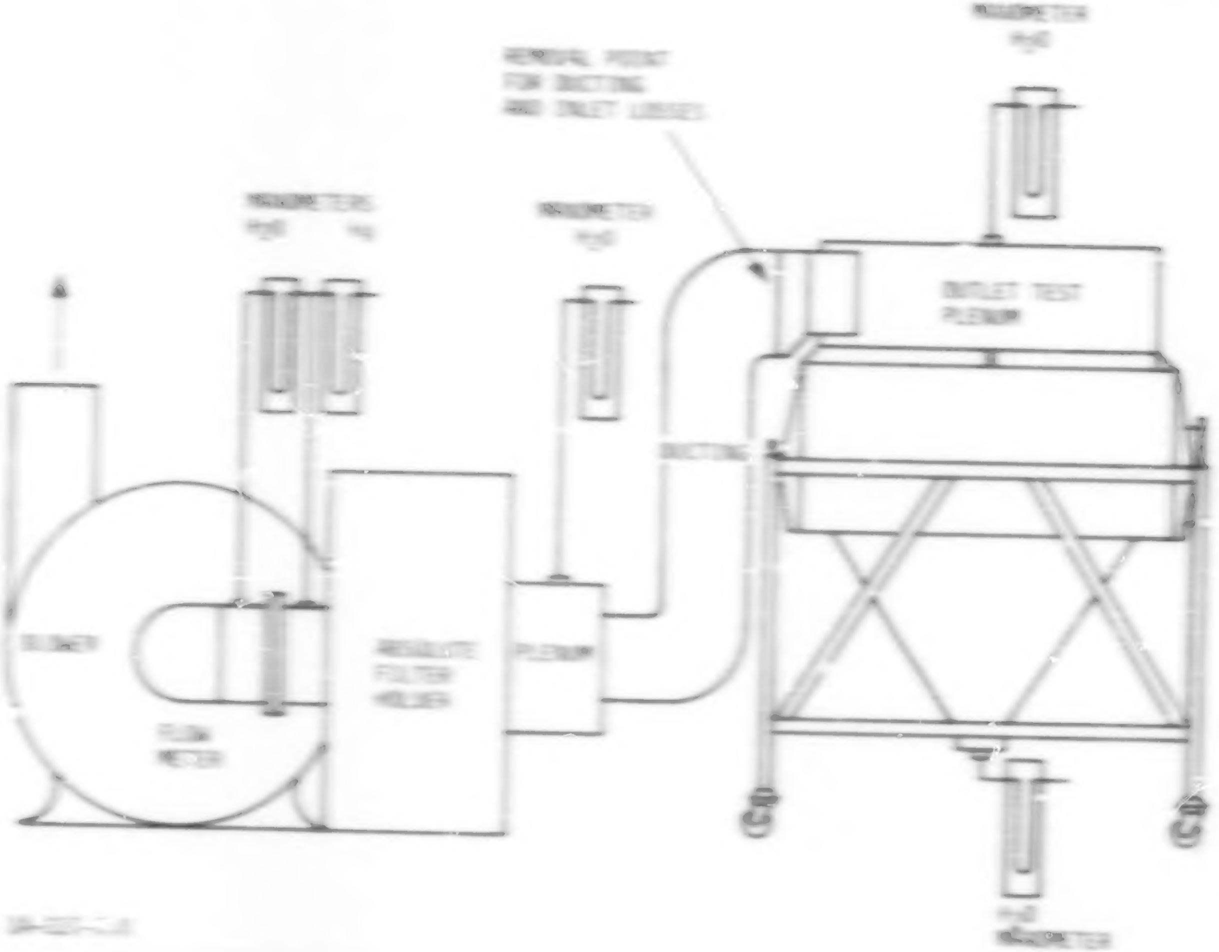
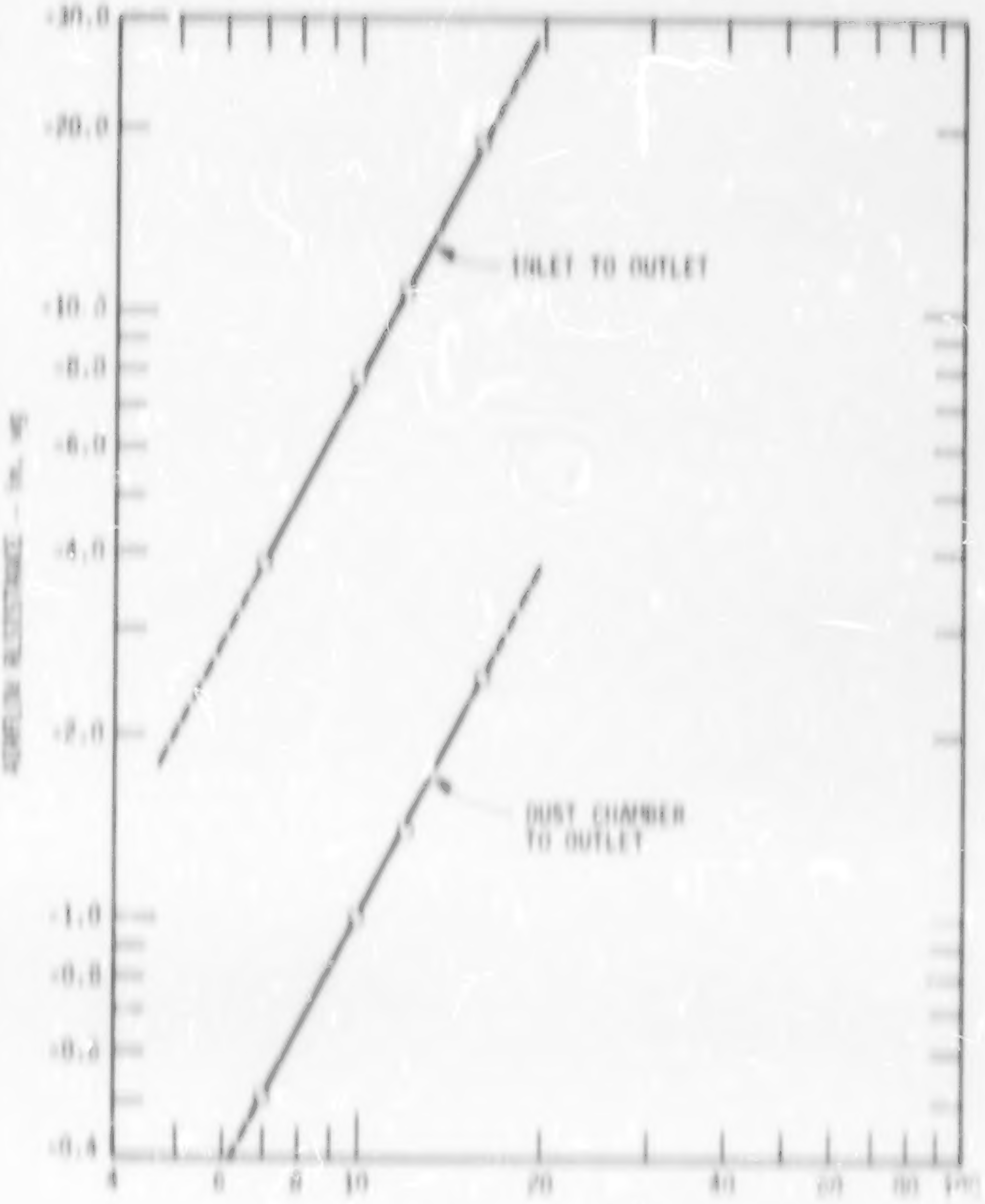

MANOMETERS
H2O Hg
MANOMETER
H2O
REMOVAL POINT
FOR DUCTING
AND INLET LOSSES
MANOMETER
H2O
OUTLET TEST
PLENUM
DUCTING
BLOWER
FLOW
METER
ABSOLUTE
FILTER
HOLDER
PLENUM
H2O
MANOMETER

Figure 3-35 Airflow Resistance Test Setup

Figure 3-36 Overall View of Collector and Setup



221-24

Figure 3-37 Ambient Airflow Resistance, Third Stage Separator

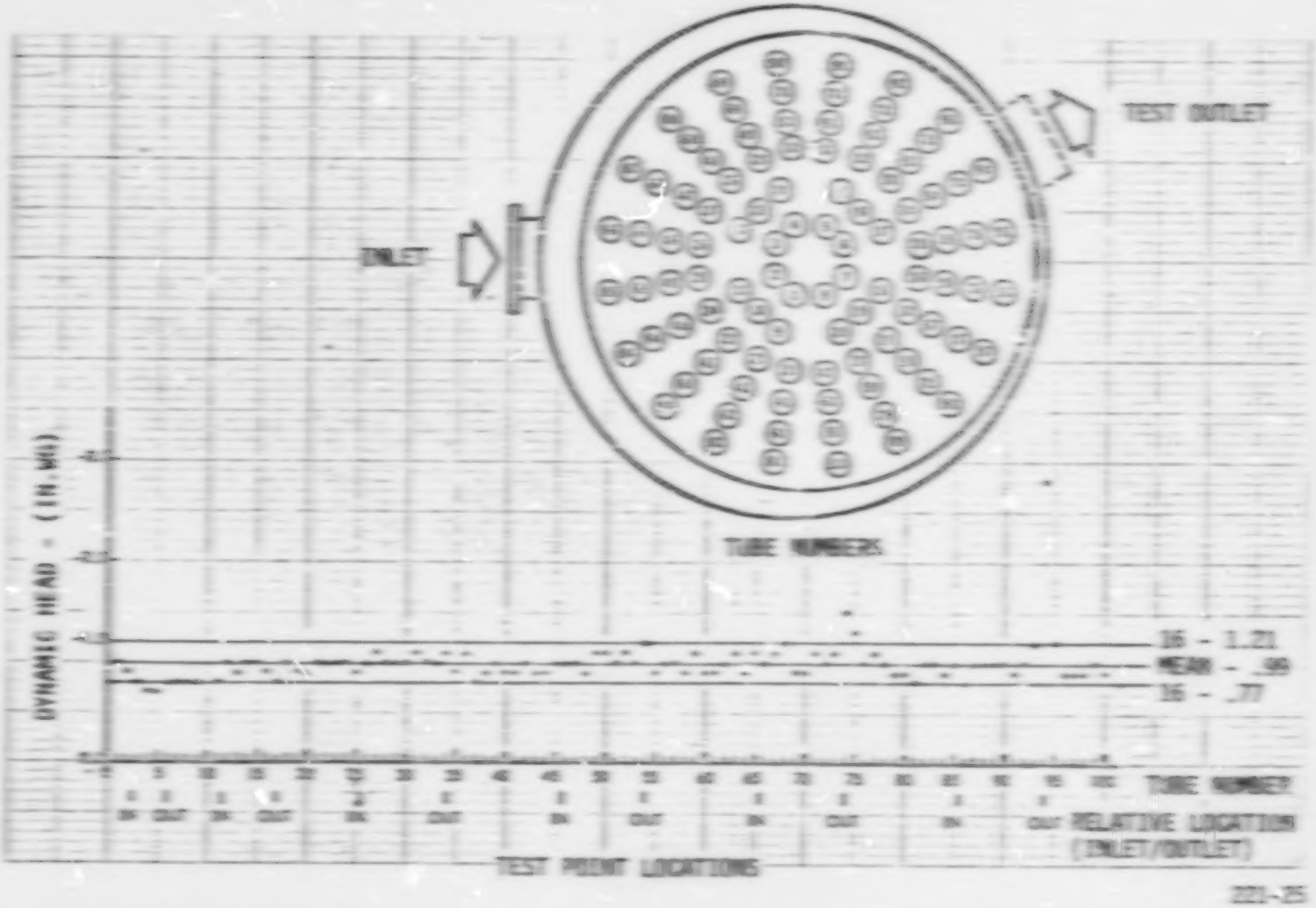


Figure 3-38 Flow Balance Test Results, Third Stage Separator

Table 3-6. DUST TEST DATA 5½-INCH CYCLONE COLD FLOW TESTS

Test time (min)	Orifice upstream (in. Hg)	Dust & feeder (lb)	Dust (lb)	Fed (gm)	Dust collected on absolute (gm)	Efficiency (percent) E
0.0	2.2	202.0	0	0	0	
10	3.0	196.5	5.5	2,497		
20	4.4	182.5	19.5	8,853		
22	4.5	180.0	22.0 22.0	9,988 9,988	1,852 1,852	81.5 81.5
22	2.2	180.0	0.0	0		
30	3.5	173.0	7.0	3,178		
32	3.7	170.0	10.0 32.0	4,540 14,528	848 2,700	81.3 81.4
32	2.2	170.0	0.0	0		
40	3.0	163.0	7.0	3,178		
50	3.8	154.8	15.2	6,901		
60	4.2	146.6	23.4	10,624		
65	4.5	142.5	27.5 59.5	12,485 27,013	2,251 4,951	81.9 81.7
65	2.2	142.5	0.0	0		
70	2.9	137.8	4.7	2,134		
80	3.4	130.7	11.8	5,357		
90	4.0	123.5	19.0	8,626		
100	4.4	116.6	25.9 85.4	11,759 38,772	2,187 7,138	81.4 81.6
100	2.2	116.6	0.0	0		
110	3.5	110.4	6.2	2,815		
120	4.1	104.0	12.6 98.0	5,720 44,492	1,119 8,257	80.4 81.4

and dust in the collection chamber or cone (34,379 gm). A discrepancy of 1772 gms of dust was unaccounted for after weighing the absolute filter and comparing it to what was collected in the hopper. Approximately 300 gm had collected at the separator inlet and the tube baffles. The remaining dust was deposited in the duct work or drawn through the absolute filters. The unaccounted for dust was assumed to have penetrated the assembly.

After the dust test, the dust samples were analyzed. The particle size analyses results are shown in Figure 3-39. The particle cutoff size (50 percent penetration) for this test was 2.1 microns. The overall efficiency, by percent weight, was 77.9 percent. There were no significant dust deposits on the individual tubes during these tests. A plot of cyclone efficiency versus stated particle size is shown in Figure 3-40.

Hot Operation During the 20-Series Tests.

For the 20-series testing the third stage separator was installed as the final hot gas cleanup stage (see Figure 3-29). The ash unloading system used for the 3½-inch tube inertial separator is similar to that of the second stage separator assembly.

Table 3-7 summarizes the testing and results of the 20-series test whose prime objectives were to pass LP-11 test requirements. Although the initial tests demonstrated the capability of the third stage separator to reduce the ash loading in the exhaust to the levels predicted [illegible]

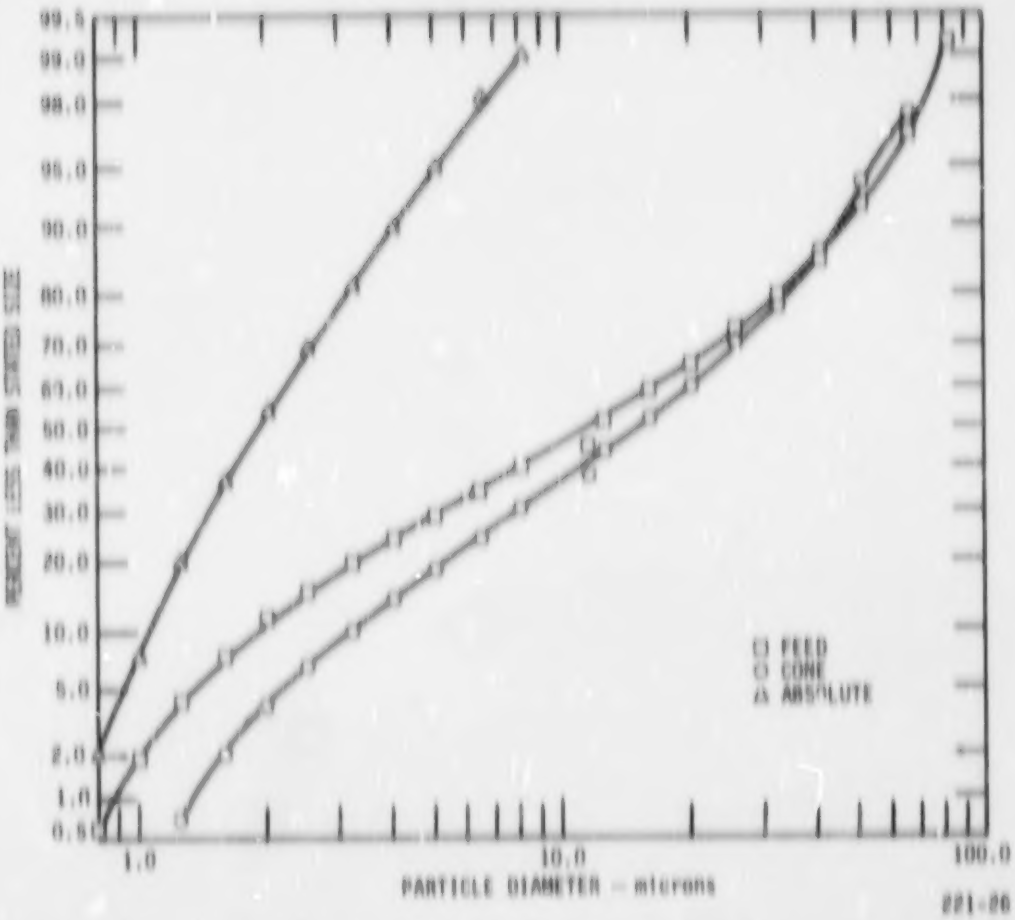


Figure 3-39 Dust Test Particle Size Analysis, Third Stage Separator

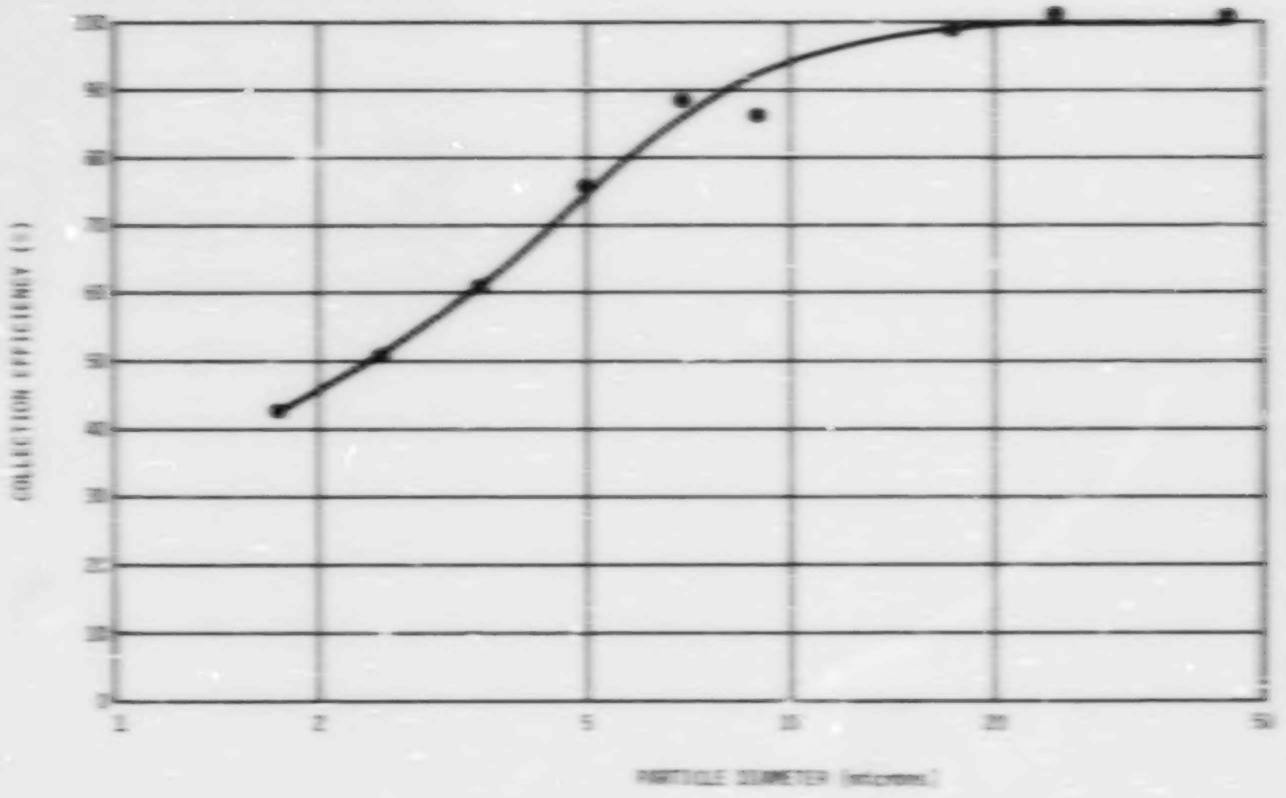


Figure 3-40 Cyclone Efficiency vs. Stated Particle Size

Table 3-7. 20-SERIES THIRD STAGE SEPARATOR TEST SUMMARY

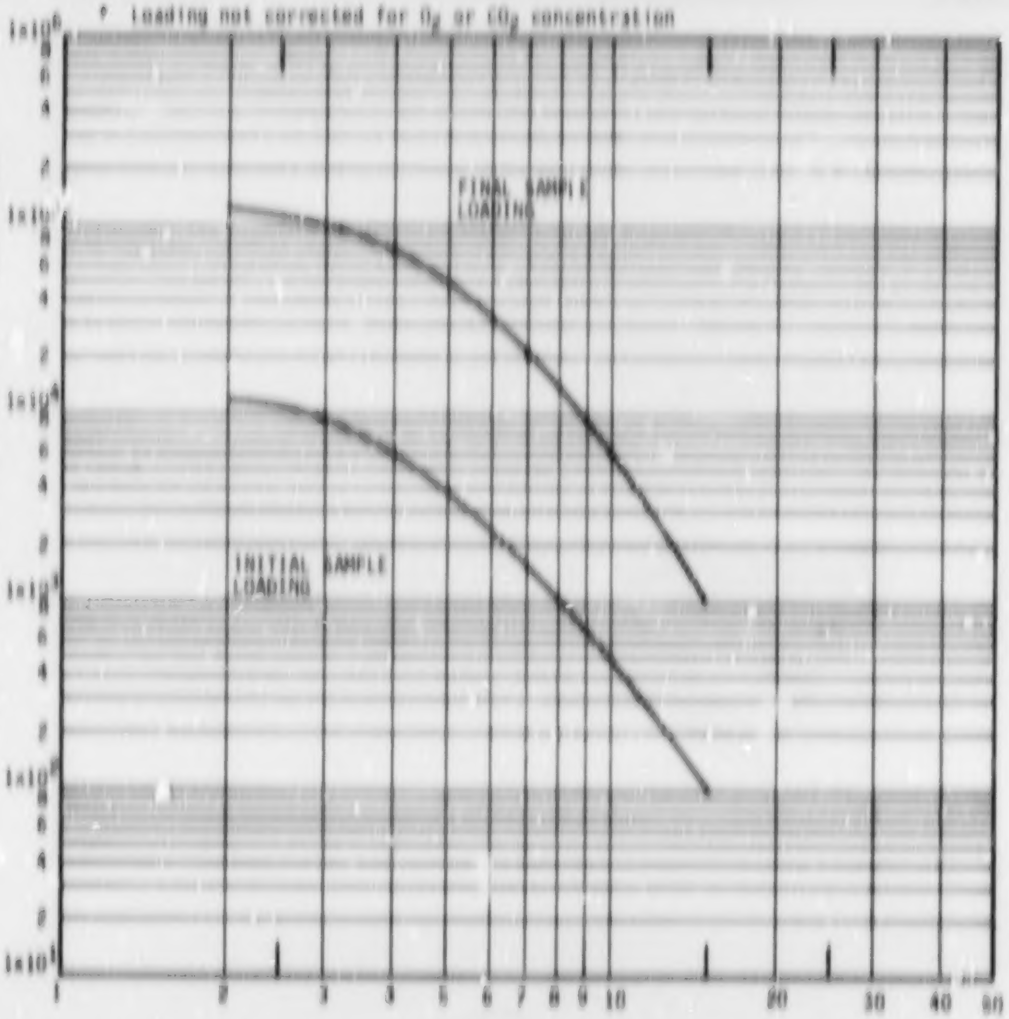
Test No.	Nominal flowrate (lb/min)	Nominal inlet temp. (F°)	No. of active tubes	Operating time (hrs)	Outlet loading (gr/scf) >2µ	>5µ	Total	Comments
20-2A & 2B	350	1450	100	3-3/4	0.0114 0.0116 0.0173	0.0001 0.0001 0.0002	0.157 0.0397 0.0272	Vibrator airlines failed & were reworked as those in the 2nd stage separator.
20-2C	352	1496	100	3½	-	-	0.0391 0.0475	Assembly was not disassembled after the test flex-line was installed in the vibrator system as it appeared to solve the duct failure problem.
20-3	350	1400	100	12.2	-	-	0.056 0.028 0.046 0.046 0.026	This test series consisted of 8 short duration runs. Post-test inspection revealed 6 plugged tubes and minor ash deposits in the remaining 94 tubes. As a result of this inspection the 26 outer ring tubes were reactivated for the remainder of the test series.

Table 3-7 (continued). 2P-SERIES THIRD STAGE SEPARATOR TEST SUMMARY

Test No.	Nominal flowrate (lb/min)	Nominal inlet temp. (F°)	No. of active tubes	Operating time (hrs)	Outlet loading (gr/scf) >2μ	>5μ	Total	Comments
2P-4A	350	1440	80 (tubes 81-100 deactivated)	33 @ 1 @ 15 @ 30	0.042 0.21 0.47	0.0066 0.12 0.33	0.044 0.58 -	As indicated by the loading data, the ash outlet cones of the 80 tubes became plugged. The common ash hopper outlet was plugged and ash was retained in the hopper. The assembly was cleaned and the bleed flow increased from 1.5 lb/min to 3 lb/min for the next test.
2P-4B	350	1433	80	50-2/3 @ 3 @ 24 @ 48	0.014 0.19 0.15	0.0036 0.10 0.05	0.081 0.50 0.41	Post-test inspection revealed successful removal of ash from the hopper during the entire test period. The cones of all 3½-inch cyclone tubes were plugged by ash deposits.
2P-5	350	1430	80 (71 with rattlers)	8.2 @ 2 @ 8	- -	- -	0.1 0.31	Post-test inspection showed all tubes with rattler free of ash deposits. 7 tubes without rattlers were plugged, and 2 tubes without rattlers were open.

by the model testing, individual plugging of the cyclone tube cones occurred during all long operating periods. The effect of tube plugging on particle size distribution is depicted in Figure 3-41. Test series 20-5 was conducted to evaluate the effectiveness of the wiper type of rattles for eliminating the ash deposits in the cones. These wipers consisted of rods that are pivoted at the inlet plane to the vane tube. A picture of the tubes after the test, Figure 3-42, clearly shows the beneficial effect of these wipers.

At the conclusion of the 20-Series tests, the 3½-inch tube inertial separator assembly was disassembled and inspected. The inspection showed the tube seals between the clean and dirty gas aisles functioned well with no evidence of leakage. There was a slight buildup of alumina on the outer diameter surface of the tube exhaust pipes which is in the dirty gas aisle. The vane area of the inertial tubes was heavily loaded with ash agglomerations as shown in Figure 3-43. A dimensional check of the 3½-inch diameter tube vanes revealed that, at the trailing edge of a majority of the vanes, the angle which the vane makes with the axial direction deviated from print by 9 degrees, resulting in a flow separation condition below the trailing edge. The edges of some of the vanes were bent to the point where the trailing edge was almost perpendicular to the axial direction of flow. The vessel assembly showed no evidence of deterioration of the inner liner by either corrosion or erosion. Wall temperatures were in the range of 150° F to 250° F during testing and showed that the Kaowool insulation performed satisfactorily. All vanes were examined and adjusted to an angle of 35 degrees and retested.



* Loading not corrected for O_2 or CO_2 concentration

221-216

Figure 3-41 Particle Loading Distribution, Test Series 20-4A

Figure 3-42 Rod Style Rattlers in 3½-Inch Tube Separator

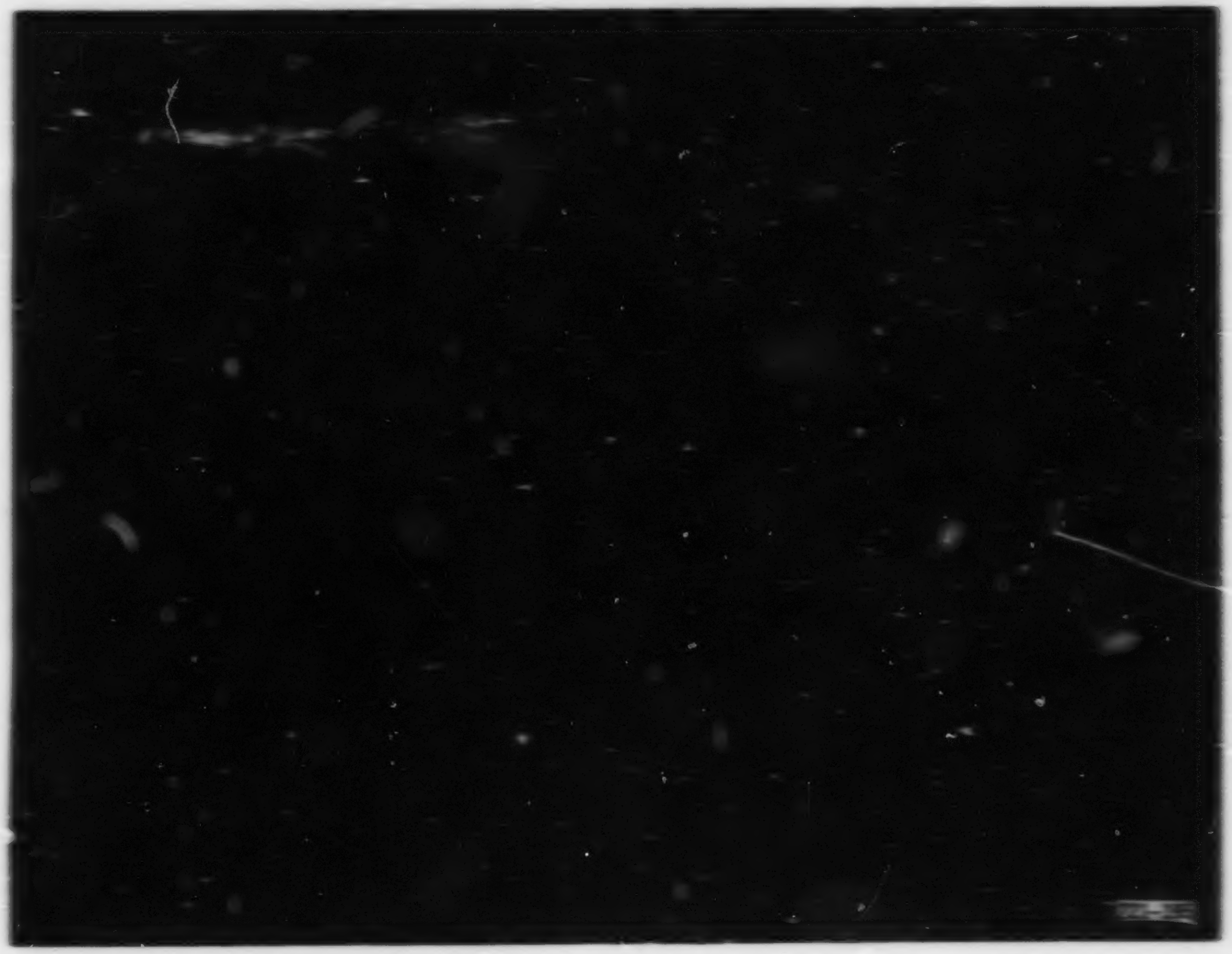


Figure 3-43 Flyash Buildup on Vanes of Third Stage Separator Tubes

The test results showed significant reduction in the amount of ash deposited at the trailing edge.

Design and Development of the Subscale Granular Filter

The subscale granular filter was fabricated and tested as a backup cleaning device for the inertial separators. The basic system design was recommended by Professor Arthur Squires, of the City College of the City University of New York, whose expertise was consulted for concept and design evaluations of granular filter devices. The design used for preliminary evaluation of this device with high temperature solid waste flyash is shown in Figure 3-44.

The active filter area is 12 inches wide and 75 inches high. At a design flow of 75 cfm the face velocity across the panel is 12 feet per minute. The selection of this velocity was based on past experimental studies of granular filters.

The filter assembly consists of a manifold module which contains the inlet, outlet, and granular material feed section, an active filter panel consisting of 120 inlet louvers and 200 outlet louvers, material collection hoppers at the bottom of the inlet, outlet, and granular material cavities, and auxiliary electrical heaters along the outside surfaces of the gas passages to make up for heat losses and maintain the assembly at the gas inlet temperature.

The louvers of the filter were held together with tie rods. Their relative position was maintained with sleeve support spacers. The ends of

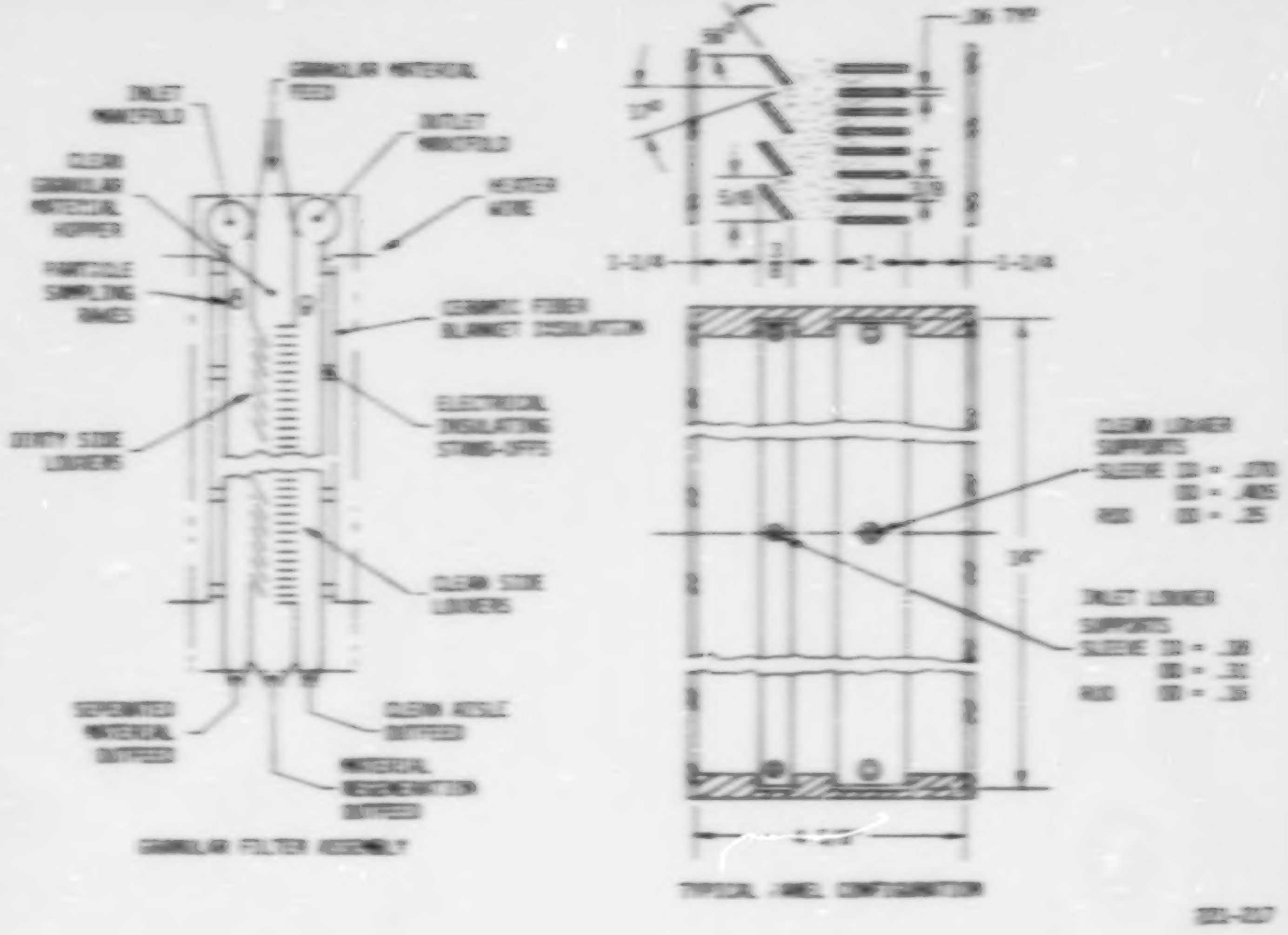

GRANULAR MATERIAL FEED
INLET MANIFOLD
OUTLET MANIFOLD
CLEAN GRANULAR MATERIAL HOPPER
HEATER WIRE
PARTICLE SAMPLING RAKES
CERAMIC FIBER BLANKET INSULATION
ELECTRICAL INSULATING STAND-OFFS
DIRTY SIDE LOUVERS
CLEAN SIDE LOUVERS
SEPERATED MATERIAL OUTFEED
CLEAN AISLE OUTFEED
MATERIAL REGENERATION OUTFEED
GRANULAR FILTER ASSEMBLY
30°
17°
5/16
.06 TYP
3/8
1-1/4
2
1-1/4
14"
4-1/2"
CLEAN LOUVER SUPPORTS
SLEEVE ID = .270
OD = .405
ROD OD = .25
INLET LOUVER SUPPORTS
SLEEVE ID = .28
OD = .31
ROD OD = .25
TYPICAL PANEL CONFIGURATION
801-027

Figure 3-44 Granular Filter Design

the louvers were set into channels. The granular material itself formed an effective seal between the ends of the louvers and the channel walls. The element support and end seal allowed relative growth between the thin louvers and the vessel side walls due to differential expansion during high temperature operation.

The design of the active element is ideally suited for enlargement of the panel size which is planned for future testing with a puffback filter cleaning system and a material regeneration system.

The inlet, dirty side, louvers were positioned at a 56 degree angle in order to make the sand surface exposed to the incoming gas normal to the louvers. This optimizes the puffback cleaning operation because the filter cake is formed on a minimum surface plane.

The principle of operation of the device is very simple. Hot, dirty gas enters the filter through the inlet manifold and flows between the louvers into the granular material (16 mesh sand was used). The path followed by the gas as it flows through the sand results in the ash being deposited on the sand surface. The cleaned gas then exits through the outlet manifold. Puffback may be used to momentarily reverse the flow, causing a layer of ash cake and particle-laden sand to be blown out to be collected at the bottom of the assembly. Clean sand enters through the top to replace that which leaves during puffback.

Granular Filter Testing-

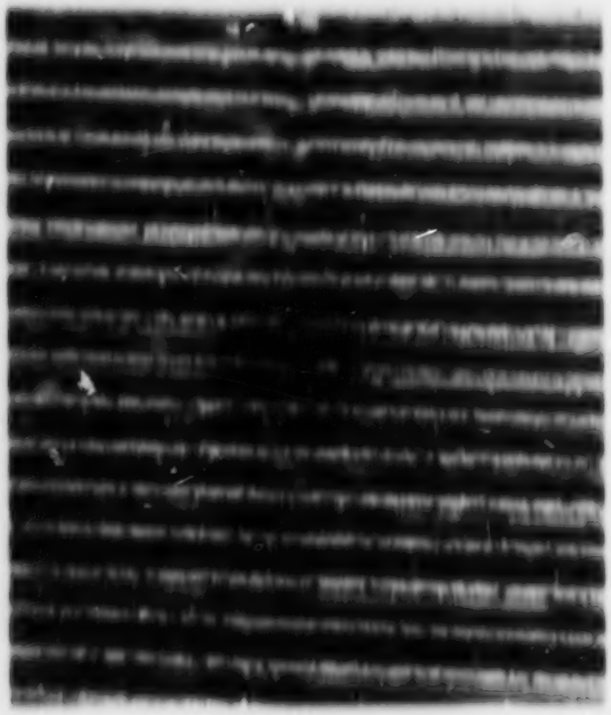
The granular filter was tested using both cold air and hot solid waste exhaust gas. The cold gas tests were used to make general checks of filter differential pressure, flyash loading characteristics, and sand size and retention ability. Testing was carried out at a filter inlet temperature of 1400° F. The effect of high temperatures on filter bed material, the effect of pressure fluctuations on the filter bed, and the total loading filtering efficiency were test objectives.

Cold Gas Testing - The cold gas testing was performed using two granular filter configurations. The first configuration (Figure 3-45) used 30 mesh sand. The angle of repose of the 30 mesh sand was such that vibration during filling caused a loss of sand from the outlet louvers. A flow test was conducted resulting in a continual loss of sand from the outlet side of the filter for all flow conditions tested. Test results are cited in Table 3-8.

As a result of the flow test, two changes were instituted: the replacement of the 30 mesh sand with 16 mesh sand, and the addition of 1/8-inch high x ¼-inch deep bars welded along the outlet louvers to form a ledge against which the sand could support itself. Cold testing was then rerun. Results are cited in Table 3-9. The changes made the filter less sensitive to vibration, and later cold flow testing at 75 acfm demonstrated a filtering efficiency of 99.29 percent which proved acceptable to the point where hot gas testing could be initiated.

Hot Gas Testing - The hot gas test setup was as shown in Figure 3-46. Three tests produced the results cited in Tables 3-10 and 3-11. During the time between test 15-4 and 15-11(a), the filter was cleaned of flyash and the sand was removed and replaced with new sand.

(A) INITIAL FLAT DESIGN



(B) FINAL DESIGN WITH
LIP ON EXIT PLANE

221-196

Figure 3-45 Granular Filter Outlet Louvers

Table 3-8. 30 MESH SAND COLD FLOW

Flow (acfm)	Filter ΔP (inches H_2O)	Comment
75	0.23	Continuous loss of sand past the louvers resulted in blowthrough at the top of the panel as hopper capacity was spent at the end of testing.
	0.30	
	0.37	
	0.45	
	0.46	
120	0.62	
	0.80	
	0.10	

Table 3-9. 16 MESH SAND COLD FLOW WITH LOUVERS

Flow (acfm)	Filter ΔP (inches H_2O)	Comment
47	0.14	Water from the compressed air system began to appear at the filter outlet.
69	0.23	
91	0.25	
108	0.47	
125	0.60	
142	0.74	
160	0.90	
173	1.01	
173	1.06	
194	1.46	

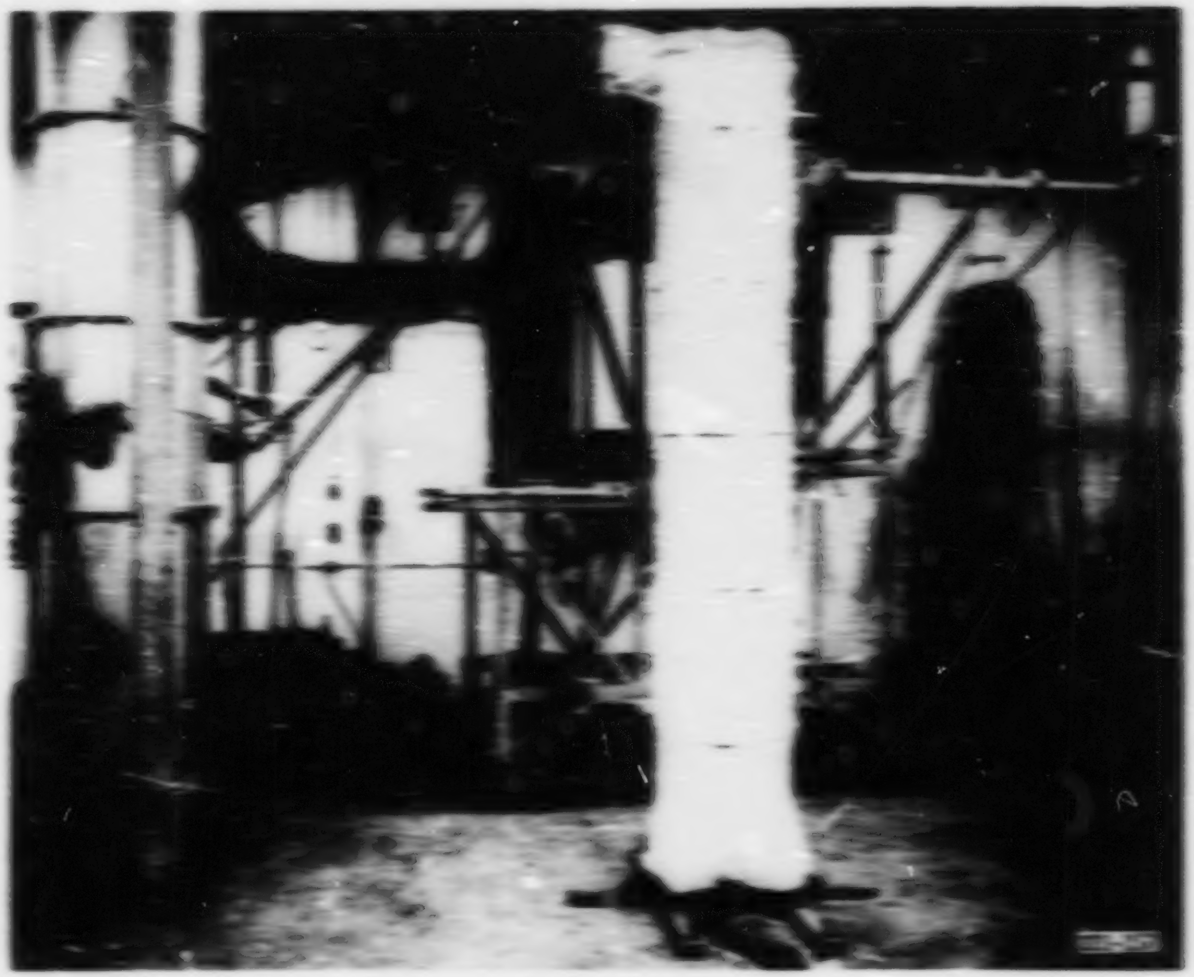


Figure 3-49. Hot Gas Test Setup

Table 3-10. HOT FLOW TEST DATA

Elapsed time (min)	Filter inlet temp. (°F)		Filter outlet temp. (°F)		Filter ΔP (inches H_2O)
	Inlet	Top	Top	Outlet	
Test 15-4 Flow = 75 acfm					
190 Diesel oil	1160	725	505	900	1.2
205 Solid waste	1225	850	560	900	1.6
220 Solid waste	1340	890	650	900	3.5
260 Solid waste	1355	890	760	900	3.5
275 Solid waste	1360	900	740	900	4.5
290 Solid waste	1365	935	750	900	5.0+
310 Solid waste	1380	980	770	900	5.0+
325 Solid waste	1460	1040	780	900	5.0+
Test 15-11(a) Flow = 75 acfm					
258 Diesel oil	1105	740	460	555	-
282 Solid waste	1200	885	595	680	1.6
287 Solid waste	1265	960	625	705	1.7
307 Solid waste	1405	965	780	860	1.7
317 Solid waste	1400	985	775	905	1.6
329 Solid waste	1400	825	850	1095	1.0
352 Solid waste	1405	770	810	1200	0.6
Test 15-11(b) Flow = 75 acfm					
104 Diesel oil	995	750	475	550	1.1
123 Diesel oil	1040	800	565	625	1.2
148 Solid waste	1140	950	650	940	1.6
155 Solid waste	1235	625	660	775	0.7
180 Solid waste	1250	730	730	1050	0.0

Table 3-11. TOTAL LOADING FILTER EFFICIENCY DATA

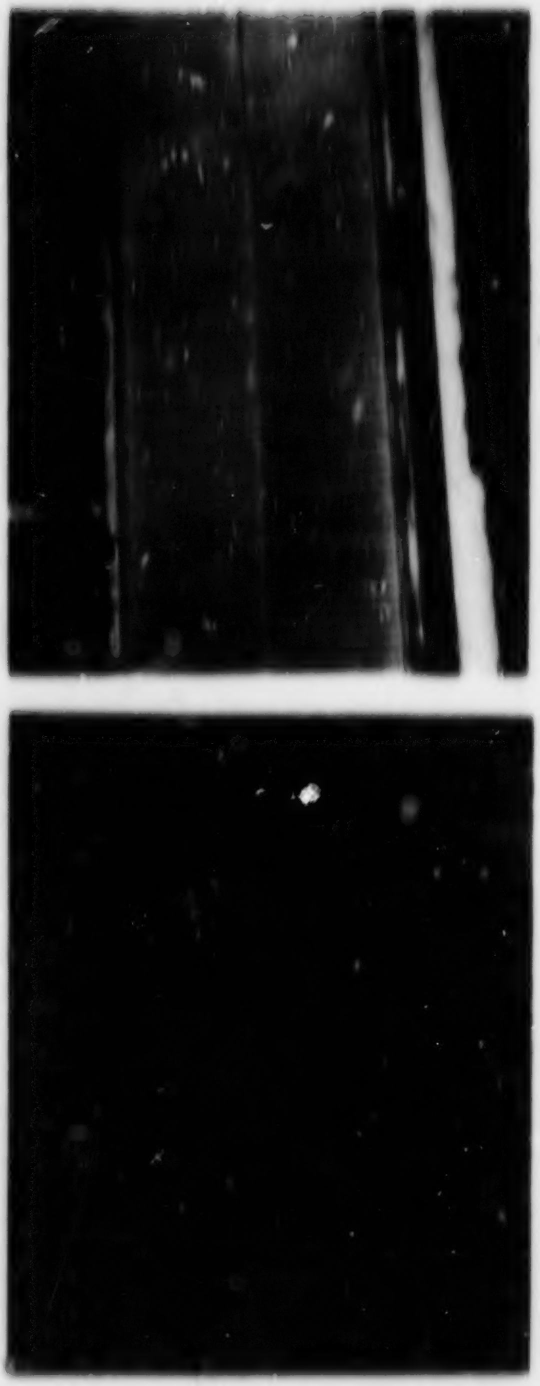
Sample No.	Total loading (gr/scf)		Efficiency (%)	Elapsed test time (min)	Comments
	In	Out			
15-4					
1	0.0336	0.002522	92.5	170 - 192	Diesel oil operation
2	0.8700	0.05144	94.15	305 - 325	Solid waste operation
15-11(a)					
1	0.07.	0.0027	96.5	256 - 268	Diesel oil operation
2	1.0571	0.2570	75.7	294 - 307	Solid waste operation
3	0.8353	0.7552	9.59	357 - 369	Solid waste operation after breakthrough
15-11(b)					
1	0.683	0.0067	98.98	128 - 140	Diesel oil operation
2	1.8883	0.7684	59.3	164 - 170	Solid waste operation after breakthrough

After tests 15-4 and 15-11(b) inspection revealed a heavy flyash cake buildup except where breakthrough occurred in the top 15 percent of the filter panel. A gradual taper in cake thickness was evident which continued uniformly to the bottom of the filter where in random spots, there was little evidence of ash deposits as depicted in Figure 3-47(a).

Final inspection of the filter panels after completion of the testing disclosed a warpage of the top eight louvers on the outlet panel. The louver spacing increased from an original 0.172 inches to as much as 0.5 inches for the top louver. Warpage also occurred on the top two louvers on the inlet panel. The spacing increased from an original 0.57 inches to as much as 0.72 inches. Further inspection of the inlet panel pointed up a structural failure in the two outer edge louver tie-down bars just below the second louver from the top. The warpage of the louvers can be eliminated by providing retaining stops on the tie bars above the last louver to prevent relative motion between the louvers.

From the data taken from the tests 15-11(a) and 15-11(b), it was evident that flyash buildup occurred to the point where the cake could no longer support the pressure differential across the panel and a breakthrough occurred at the top of the panel where the louvers were spaced at a greater distance than those below. Figure 3-47(b) shows evidence of the breakthrough where an absence of flyash cake is noticeable.

The hot gas test runs were initiated using diesel oil, and the panels heated to an outlet temperature of 500° F to 600° F. The panel heaters were connected to a power source which supplied 0.7 to 1.8 kW during



(A) WITHOUT BREAKTHROUGH

(B) WITH BREAKTHROUGH

221-198

Figure 3-47 Flyash Buildup at Inlet Louvers

the diesel oil heatup and up to 4.8 kW during solid waste operation. Filter inlet temperatures reached 1400^0 F with no sand agglomeration noticeable on either the inlet or outlet face of the sand. However, despite the power input of 4.8 kW, the outlet temperatures never met the specified 100^0 F less than inlet temperature requirement cited in the Test Plan.

The 15-4 test indicated that a panel differential pressure of 5 inches of water is attainable on an as-designed panel without breakthrough or loss of sand due to combustor induced pressure oscillations. This test demonstrated that the granular filter is capable of building up a filter cake which is insensitive to pressure fluctuations produced by a fluidizing bed.

The total loading filter efficiencies are listed in Table 3-11. The loadings for tests 15-11(a) and (b) reflect the sharp difference in outlet flyash loading after breakthrough occurs. The majority of the solid waste operation was typified by sample 2 of test 15-4. Figures 3-48 and 3-49 are submitted as an example of particle removal efficiency and particle loading distribution as a function of particle size.

DESIGN AND DEVELOPMENT OF THE RESIDUE REMOVAL SYSTEM

Determination of Need for Residue Removal System (Task LP-5)

A total of 247 hours of testing was conducted to determine the requirement for residue removal as the result of solid waste combustion within a fluidized bed. The quantity, size, growth or attrition, the nature

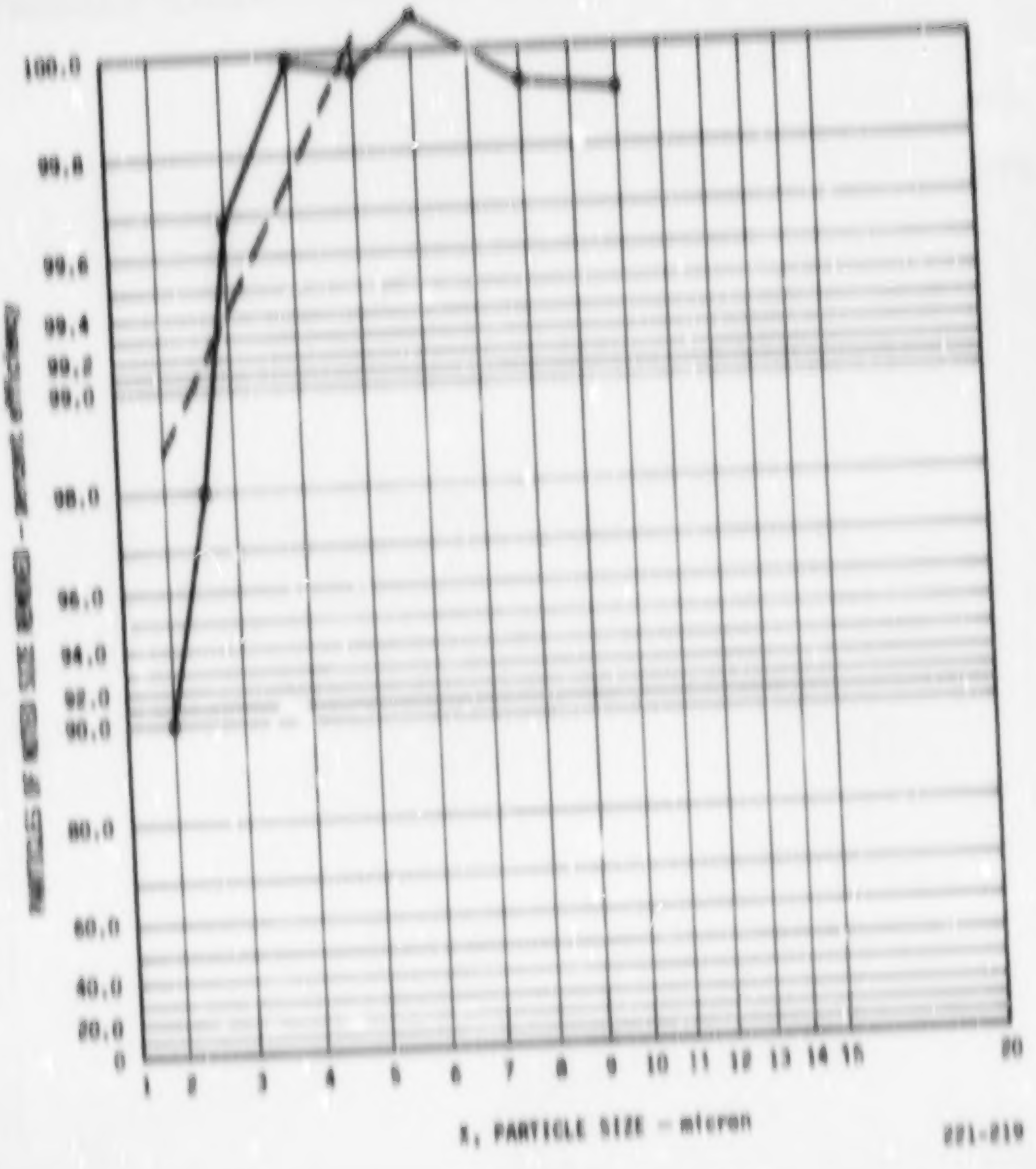


Figure 3-48 Granular Filter Fractional Efficiency

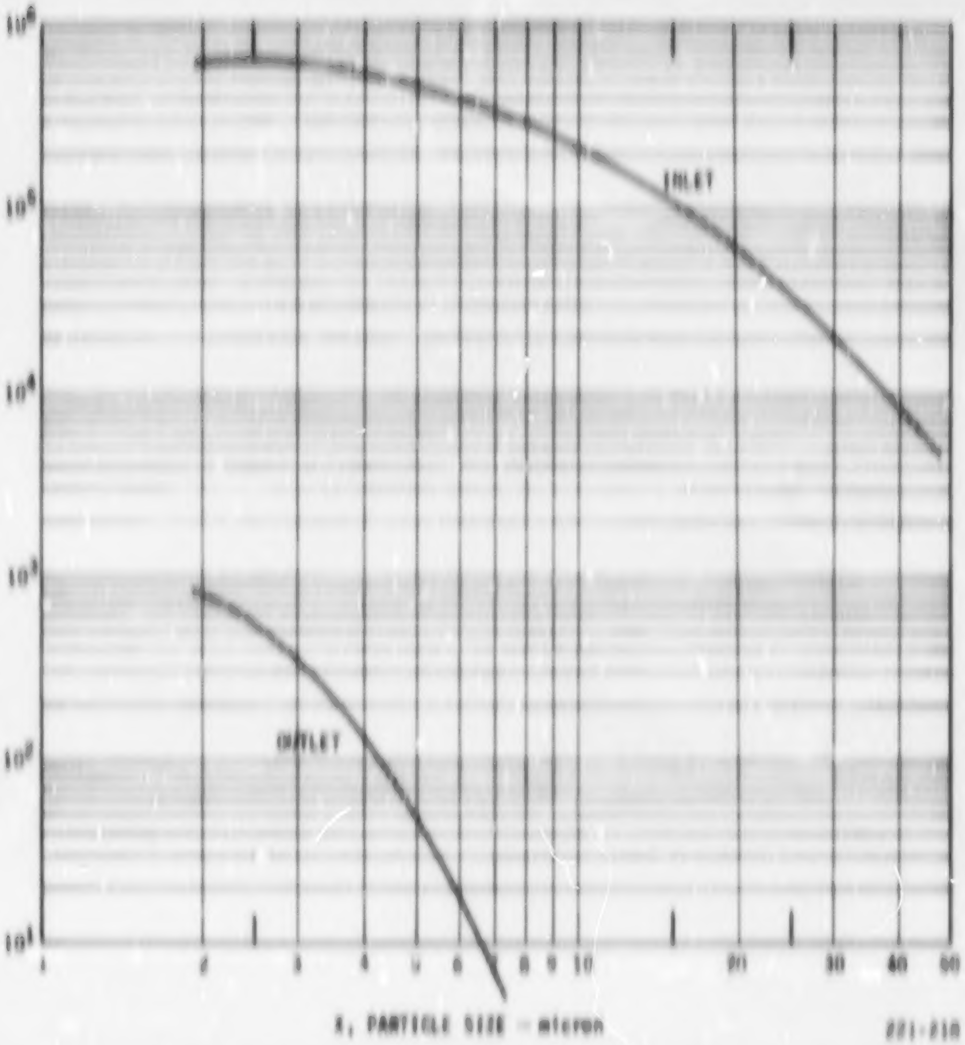


Figure 3-49 Size Distribution of Material Penetrating and Entering the Panel Filter

of the residue, handling considerations, and an evaluation of the exhaust system separators constituted the scope of these tests. The entire testing sequence was performed with the CPC designed Model No. 3 combustor. This vessel (see Figure 3-50) has an internal diameter of 20 inches and an outside diameter of 32 inches, with 13½ feet between the air distributor and the exhaust pipe. The inner liner was composed of 16 gauge, 310 stainless steel; the outer shell is made of 11 gauge carbon steel. The 6-inch annular space between the internal and outside diameter was packed with Kaowool insulation to reduce heat loss. Solid waste was introduced into the fluidized bed through a 2-inch feed pipe which entered the bed just above the air distributor. The solid waste was fed to the feedpipe pneumatically from a 5-inch feeder valve. The average feedrate was controlled by the desired bed temperature setting in the control system which fixed the on/off periods of feed. Provisions also existed for introducing fuel oil into the bed. A schematic of the Model No. 3 combustor test setup and a photograph of the solid waste feed system are shown in Figure 3-51 and 3-52, respectively. Details of data and measurements required during the tests are summarized in the following paragraphs.

Fluid Bed Combustor Bed Test Conditions.

For the 240 hours of testing, during which solid waste was used as fuel, the initial fluidized bed was composed of 16 mesh beach sand. The size distribution of the starter sand is shown in Figure 3-53. For the first 120 hours of testing the bed level was allowed to float. During the next 60 hour test period, the bed was maintained at 2 feet.

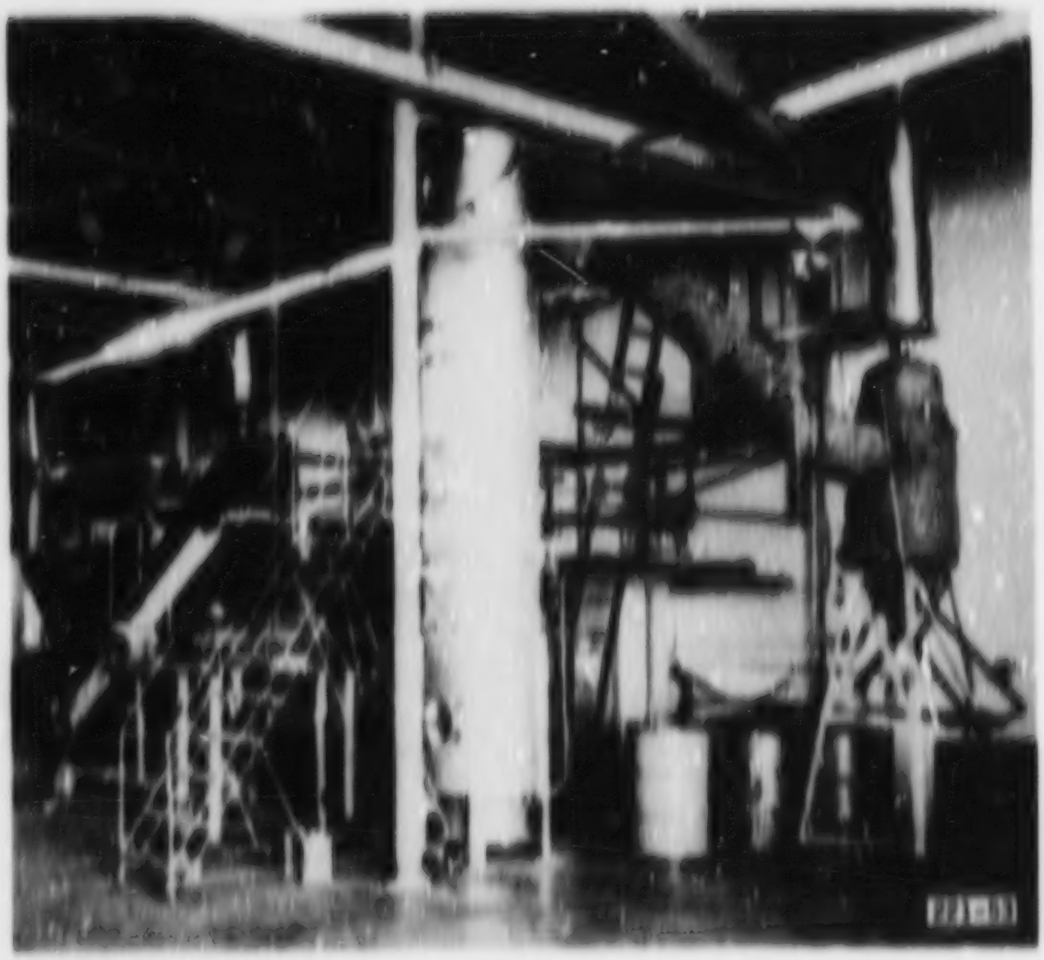


Figure 3-50 Model No. 3 Installation

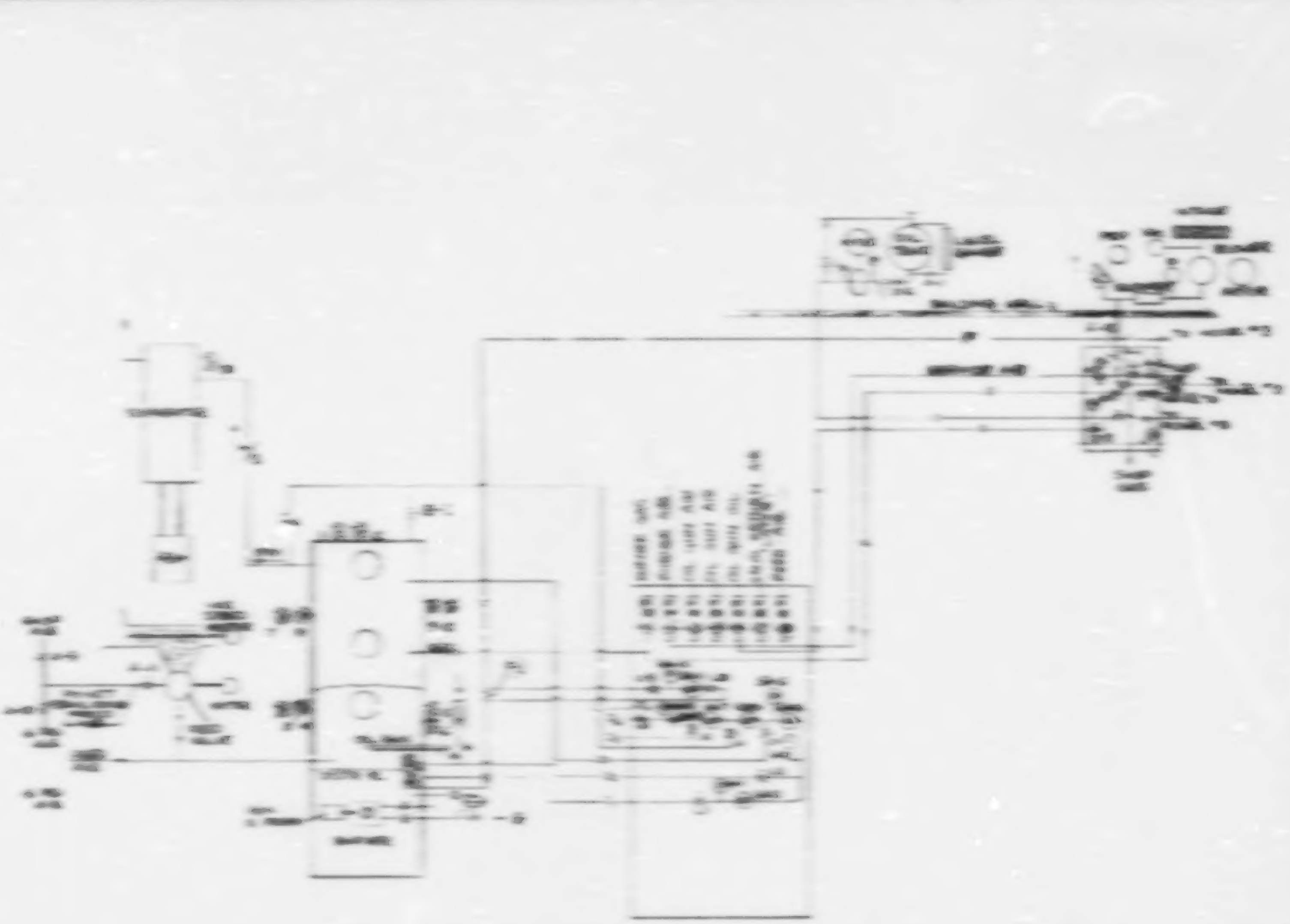


Figure 3-61 Model No. 3 System Schematic

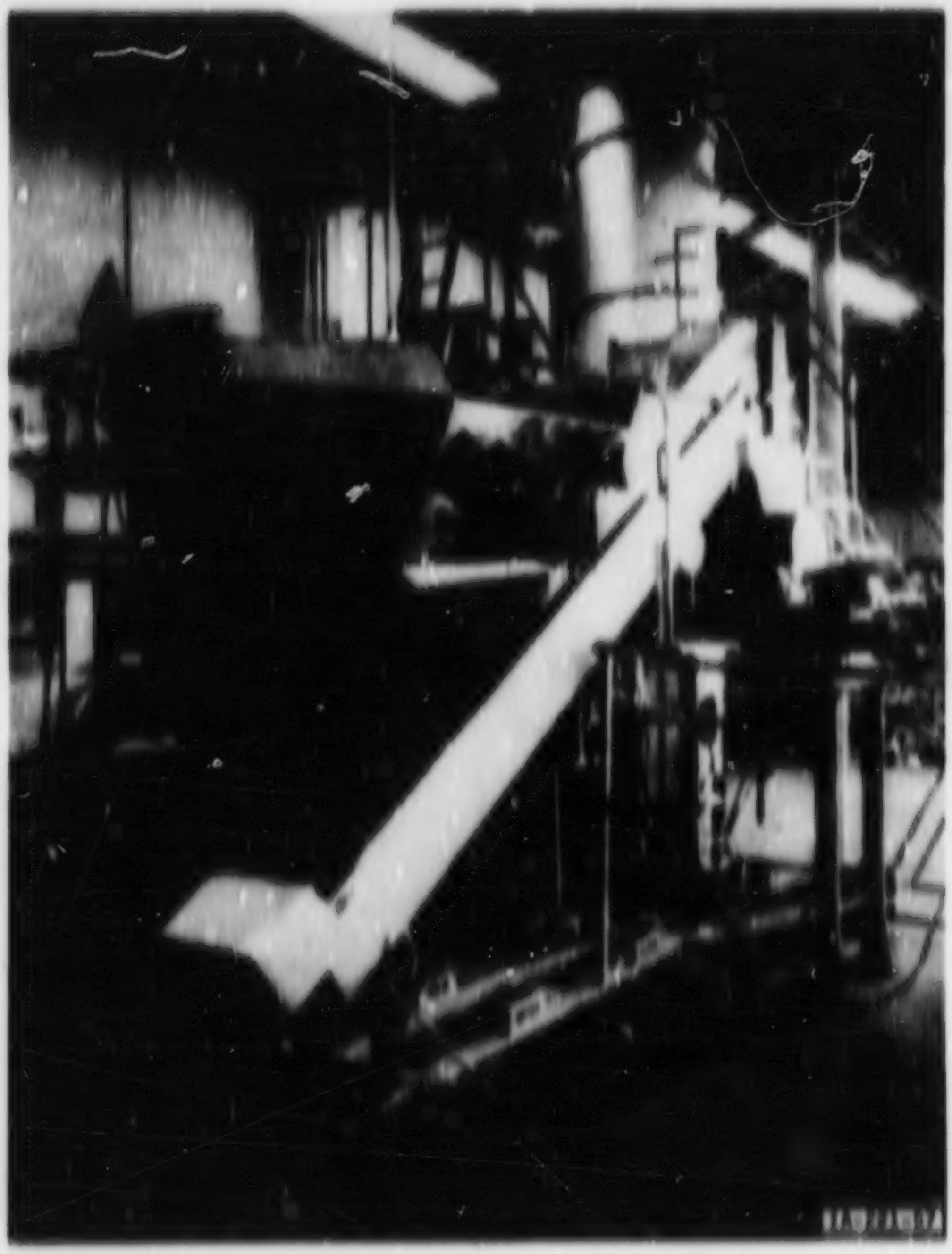
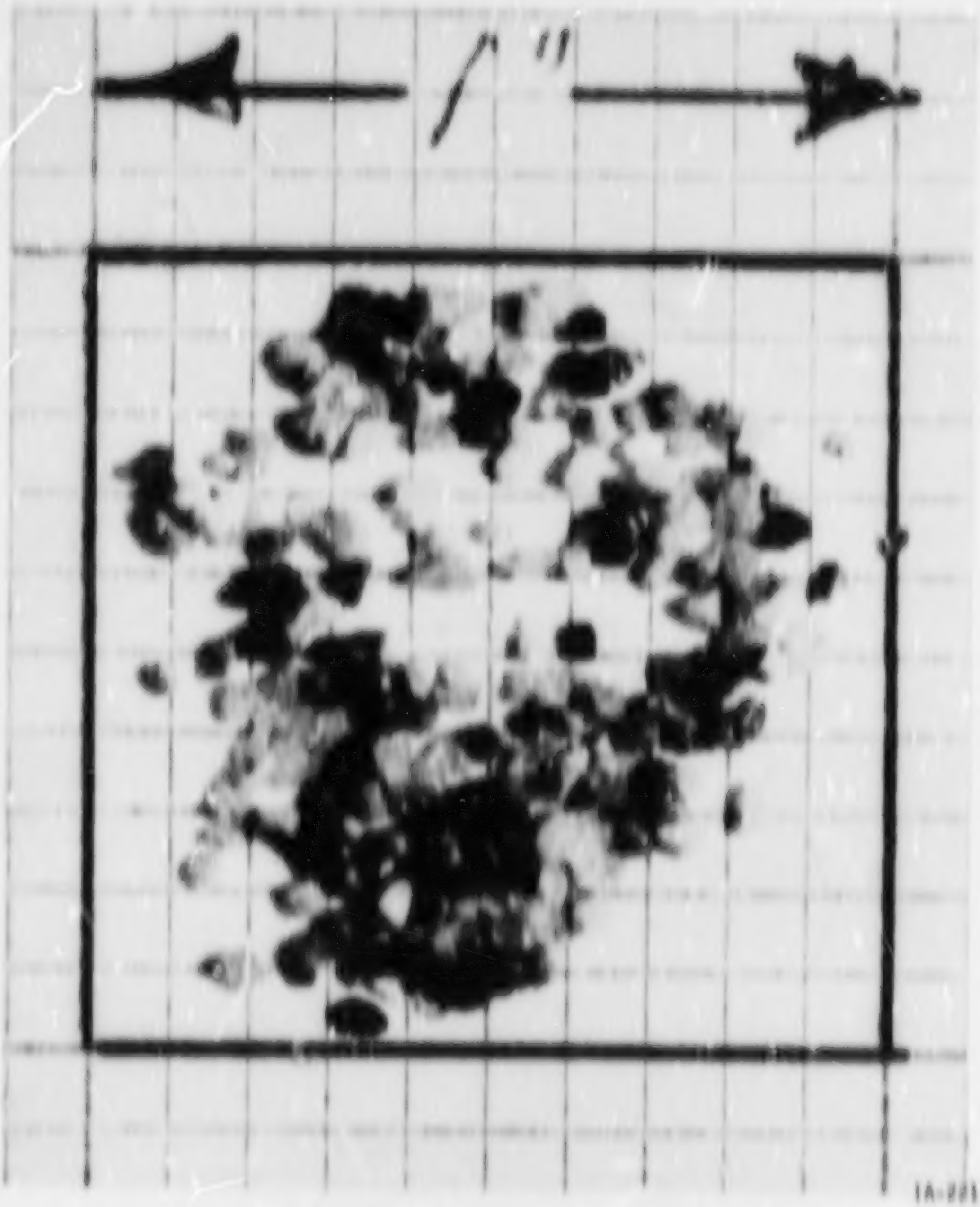


Figure 3-52 Model No. 3 Solid Waste Feed



IA-221-81

Figure 3-53 16 Mesh Beach Sand

For the final 60 hour test period, the bed level was held at 3 feet. During a subsequent 7-hour test, during which diesel oil was used as fuel, the bed level was again maintained at 2 feet. During all tests, the air flow through the bed was maintained at 265 scfm to provide a nominal superficial velocity of 7 ft/sec at bed temperature. During the entire test the bed temperature was maintained at 1425 ± 10° F, except for some momentary delays caused by plugging in the feedline. This caused the bed temperature to drop below 1400° F, and the test clock to be stopped. However, these problems were easily solved and the testing resumed without further incident. A typical temperature record of the bed and freeboard is shown in Figure 3-54. Of interest is that the freeboard temperature is normally higher than the bed temperature and generally decreases with increased bed depth.

Bed Characteristics-

Solid Waste Consumed - A total of 32,074 pounds of solid waste was consumed. Twenty-three samples of the material consumed were taken for limited analysis of moisture content, total inerts, size distribution of inerts, and metal content. The results of this analysis are cited in Table 3-12.

Bed Size Distribution - A simplified size distribution of 16 mesh starter beach sand and the size distribution after 120, 180, and 240 hours of bed operation is given in Table 3-13. As indicated by Table 3-13, the steady state bed was reached prior to 120 hours of operation. The aged bed material is shown in Figure 3-55.

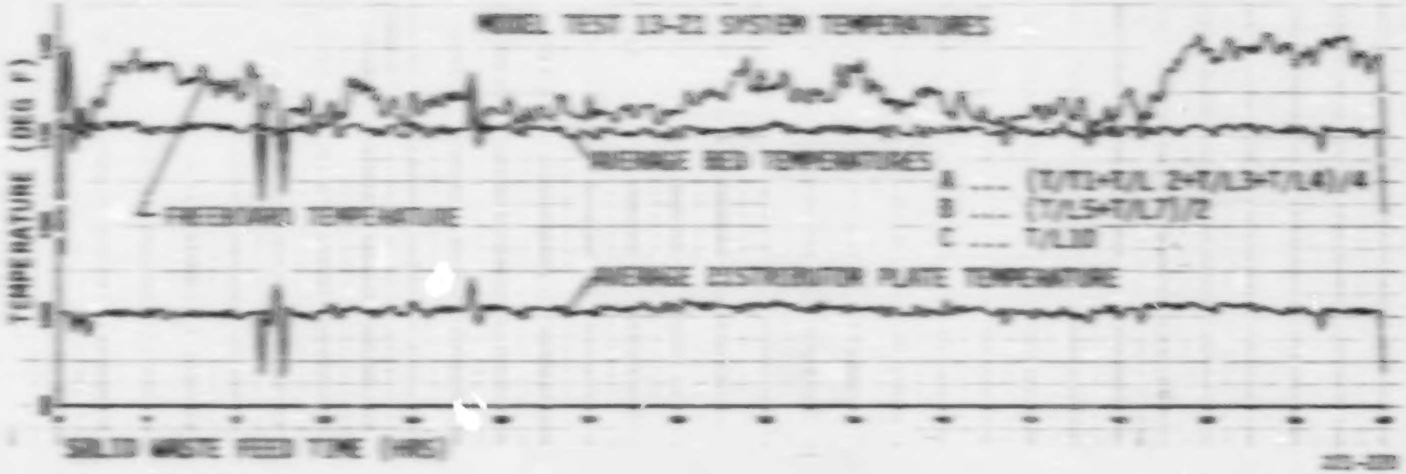


Figure 3-58 Temperature History (13-5 Testing)

Table 3-12. SOLID WASTE SAMPLE DATA

Test time (hrs)	Solid waste consumed (lbs)	Moisture content (%)	Inert total (%)	Inert metal (%)	Inert distribution (%)	Size (U.S. Standard mesh)
0 - 120	15,006	20.9	11.27	0.26	22.11 33.72 44.17	>16 16>30 <30
120 - 180	16,479	28.9	6.06	0.09	25.07 33.26 41.67	>16 16>30 <30
180 - 240		23.4	10.02	0.08		

Table 3-13. BED MATERIAL SIZE DISTRIBUTION

Size (U.S. Standard mesh)	Beach sand (16 mesh starter) (%)	120 hour (%)	180 hour (%)	240 hour (%)
>16	25.37	34.61	34.21	35.89
16-30	72.76	53.88	53.06	52.58
<30	1.87	11.51	12.73	11.53

Table 3-14. INCIPIENT FLUIDIZATION VELOCITY

Test time (hrs)	Incipient fluidization velocity (ft/sec)
0	1.68
120	1.54
180	1.43
240	1.43

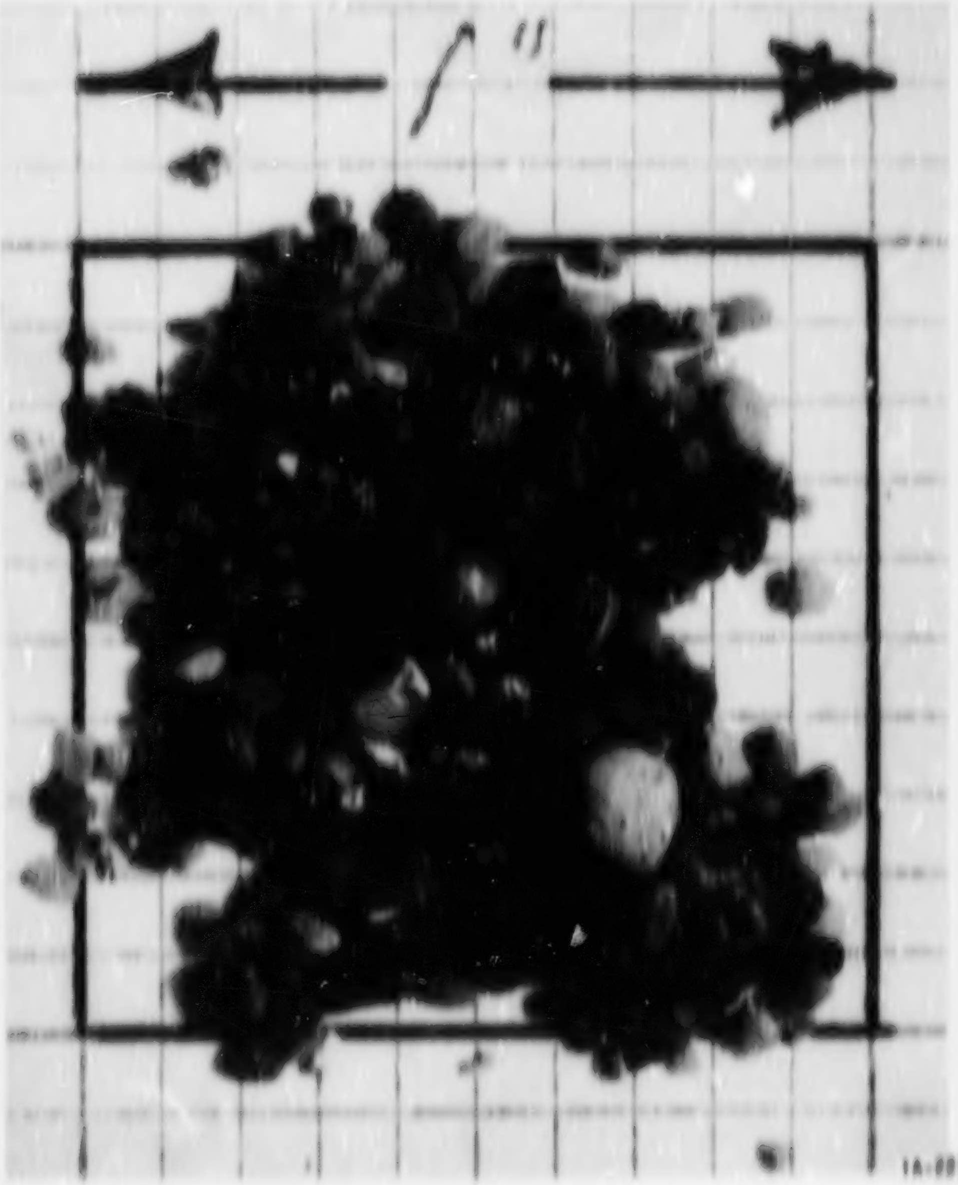


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Figure 3-55 Aged Bed Material

At the conclusion of the 240 hour test the bed material was passed through a ¼-inch screen. Approximately 5/8 pounds of the 610 pounds of bed material sieved was greater than ¼-inch in size. A comparable percentage of large particles was found in the samples removed from the operating bed indicating that these items are evenly distributed throughout the bed. The large particles consisted of rocks, ceramic pieces, clinker pieces, bolts and miscellaneous items. This small quantity (5/8 pounds) compared to the 37,000 pounds of solid waste consumed is not expected to cause a problem.

A 7-hour attrition test using diesel oil as fuel was performed in an effort to establish the effect of bed operation on bed media size changes. The test was conducted at a bed temperature of 1400° F and a superficial velocity of 7 ft/sec. Size distribution and weights were analyzed prior to and following the test. Three pounds of the 183 pounds of bed material greater than the 16 mesh size were worn away during this test.

Metals - Based on 22 solid waste samples, 86 pounds of metal were fed into the combustor during the 240 hour test. Fifty-five pounds of metal were removed as samples and for height maintenance during bed operation. Nineteen pounds were present at the end of testing. Therefore, only 12 pounds of metal were consumed during the test. A metal attrition rate of 0.003 pounds oxidized per pound present per hour was calculated from this information. The 7-hour bed material attrition test described above was also used to verify this value.

In that test, the metal attrition rate was 0.005 pounds oxidized per pound present per hour. This value is comparable to the calculation made during the 240 hour test.

Minimum Fluidizing Velocity - An important parameter in bed material evaluation is minimum fluidizing velocity. Table 3-14 displays the manner in which this parameter varied with time. The data, taken at ambient conditions, indicates that the population of fine particles (Table 3-13) is the dominant factor in bed activity, which improved with time during the test.

Bed Depth - During the first 120 hours of testing, the depth was allowed to establish its own level. The depth was, therefore, determined by a balance between inerts introduced with the solid waste and elutriation. Figure 3-56 shows the bed variation (ΔP) and solid waste inert percentage as a function of test time. As indicated in this figure, the lowest level of solid waste inerts recorded during the test was 6 percent. The 6 percent solid waste inert level was the lowest experienced during the contract period and probably occurred because of excessive handling of the solid waste during the early part of the test. However, a low solid waste inert level is a possibility and consideration should be given to shallow-bed operation and bed material addition.

Between 120 and 180 hours the bed was maintained at the 2 foot level (static depth) as determined by bed pressure drop. To accomplish this, 494 pounds of bed material was drained from the operating bed. For

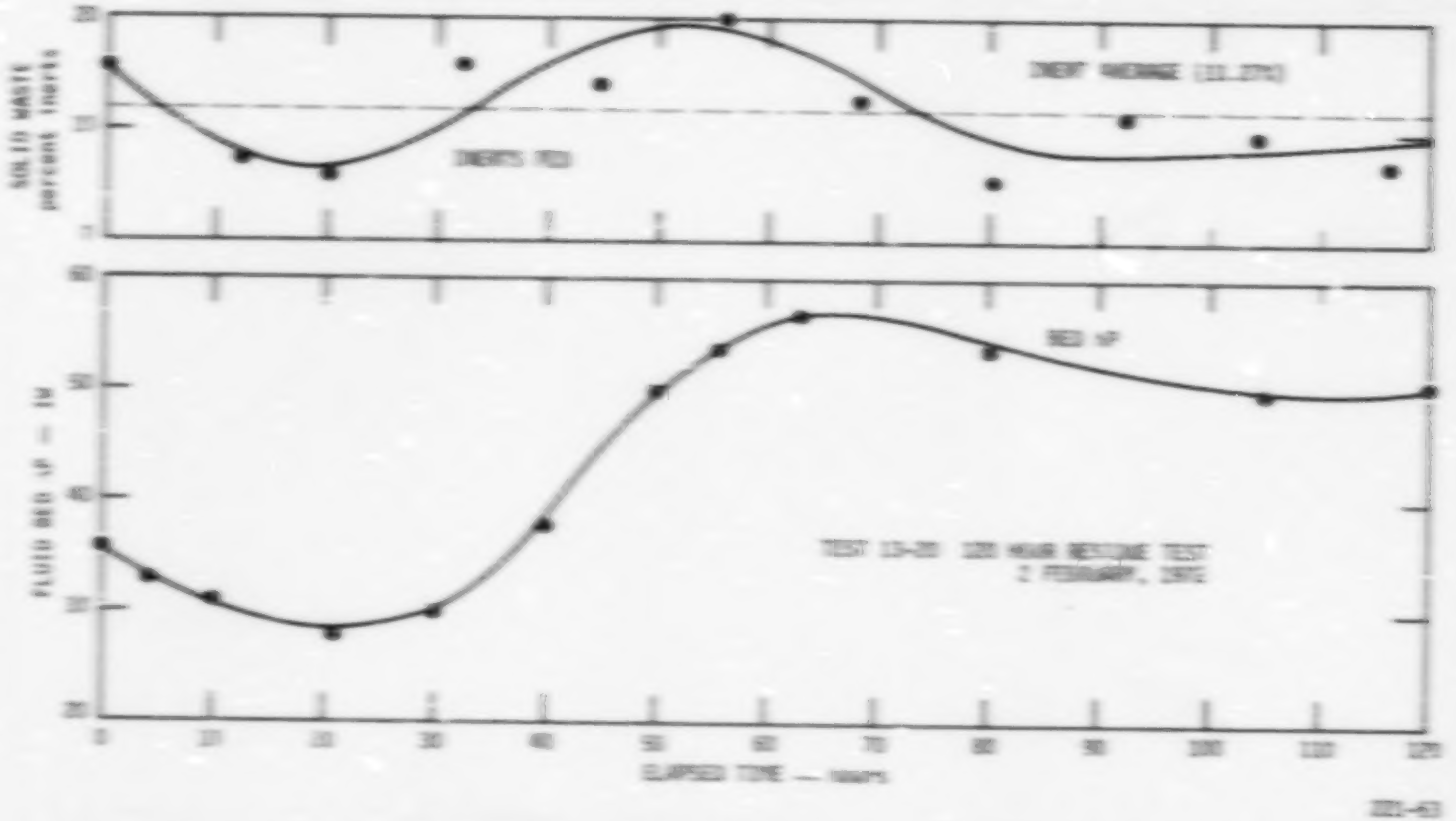


Figure 3-56 Bed ΔP (Volume) and Inerts Added

the final 60 hours, the bed depth was held at 3 feet. During this period, 496 pounds of bed material was removed in order to maintain the desired level.

Bed Density - Density of the starter bed was 100 pounds per cubic foot. At the end of the first 120 hours the density had stabilized at 89 pounds per cubic foot.

Elutriation - In the fluidized bed combustion process, the lighter particles are constantly being carried away in the exhaust gases. The flyash particles ($<150\mu$) are readily elutriated. Other inert particles introduced into the fluidized bed in the solid waste (of which the steady state bed is composed), are elutriated in relation to size, freeboard height, gas velocity, and bed size.

In the model test, elutration for the 2 foot and 3 foot bed depths was 840 and 1189 pounds of material, respectively, over the two 60-hour periods. Also, the particle size of the elutriated material captured by the first stage separator was larger for the 3 foot bed: 13.3 percent >30 mesh compared to 4.8 percent >30 mesh for the 2 foot bed.

Chemical Analysis - Samples of the original bed material, aged bed material, flyash, and exhaust pipe clinker were subjected to spectrographic analyses. The results of this analysis are summarized in Table 3-16.

Table 3-15. SPECTROGRAPHIC ANALYSIS (SEMI-QUANTITATIVE)[a]

Element	16 Mesh beach sand	120 hr bed	240 hr bed	Flyash after 240 hrs	Exhaust pipe clinker
Iron	1.00	2.00	1.60	3.00	3.00
Copper	0.0003	0.12	0.20	0.10	0.15
Nickel	0.001[b]	0.002	0.001	0.01	0.04
Chromium	0.02	0.08	0.25	0.07	0.10
Aluminum	4.50	3.50	3.00	10.00	Major[c]
Lead	0.001	0.08	0.20	0.10	0.10
Tin	0.001[b]	0.004	0.02	0.03	0.06
Zinc	0.10[b]	0.10	0.10	0.15	0.20
Cobalt	0.001[b]	0.001[b]	0.001[b]	0.001[b]	0.001[b]
Manganese	0.01	0.08	0.03	0.25	0.25
Molybdenum	0.001[b]	0.001[b]	0.001[b]	0.002[b]	0.001[b]
Silicon	Major[c]	Major[c]	Major[c]	Major[c]	10.00
Silver	0.0001[b]	0.001	0.002	0.002	0.002
Vanadium	0.002	0.004	0.005	0.006	0.01
Magnesium	0.15	0.30	0.70	1.20	0.80
Calcium	0.35	10.00	10.00	Major[c]	6.00
Titanium	0.05	0.15	0.20	0.30	0.25
Sodium	2.00	6.00	5.00	5.00	2.00
Potassium	3.00	2.00	2.00	2.00	1.00
Strontium	0.03	0.02	0.02	0.02	0.01
Zirconium	0.007	0.02	0.01	0.01	0.004
Boron	0.001	0.05	0.03	0.02	0.01
Barium	0.15	0.18	0.20	0.10	0.10

[a] All values expressed in percent

[b] Less than indicated value

[c] More than 10 percent

Generally, bed material had stabilized by 120 hours and a slight increase in trace elements was visible with time. A pronounced increase (from 0.35 to 10 percent) in calcium was observed. The exhaust pipe clinker was chemically very similar to the flyash except the aluminum content was much higher and the silicon content was lower.

Exhaust System-

The secondary objective of the 240-hour test was the evaluation of the exhaust system including material separators. It was initially found that a very hard gray clinker formation occurred at the first impingement point (sharp turn) in the exhaust pipe. The composition of this formation, shown in Table 3-15, was principally aluminum with lesser amounts of silicon present as the secondary element. The formation rate was approximately 0.25 pounds per 100 pounds of solid waste consumed.

The first device used in breaking up this formation was a hollow impingement plate which was periodically shocked by water circulation. This configuration, shown schematically in Figure 3-57, successfully flaked the clinker off, but soon failed structurally as a result of thermal shock.

After 49½ hours of test operation, the clinker handling concept was changed. The impingement plate was inclined at an angle of 45 degrees to the incoming gas, and a settling chamber and a sand/ash removal line were added to the test configuration. This configuration operated satisfactorily for the duration of the test. The inclined plate removed 93 percent of all hard clinker generated while the remaining

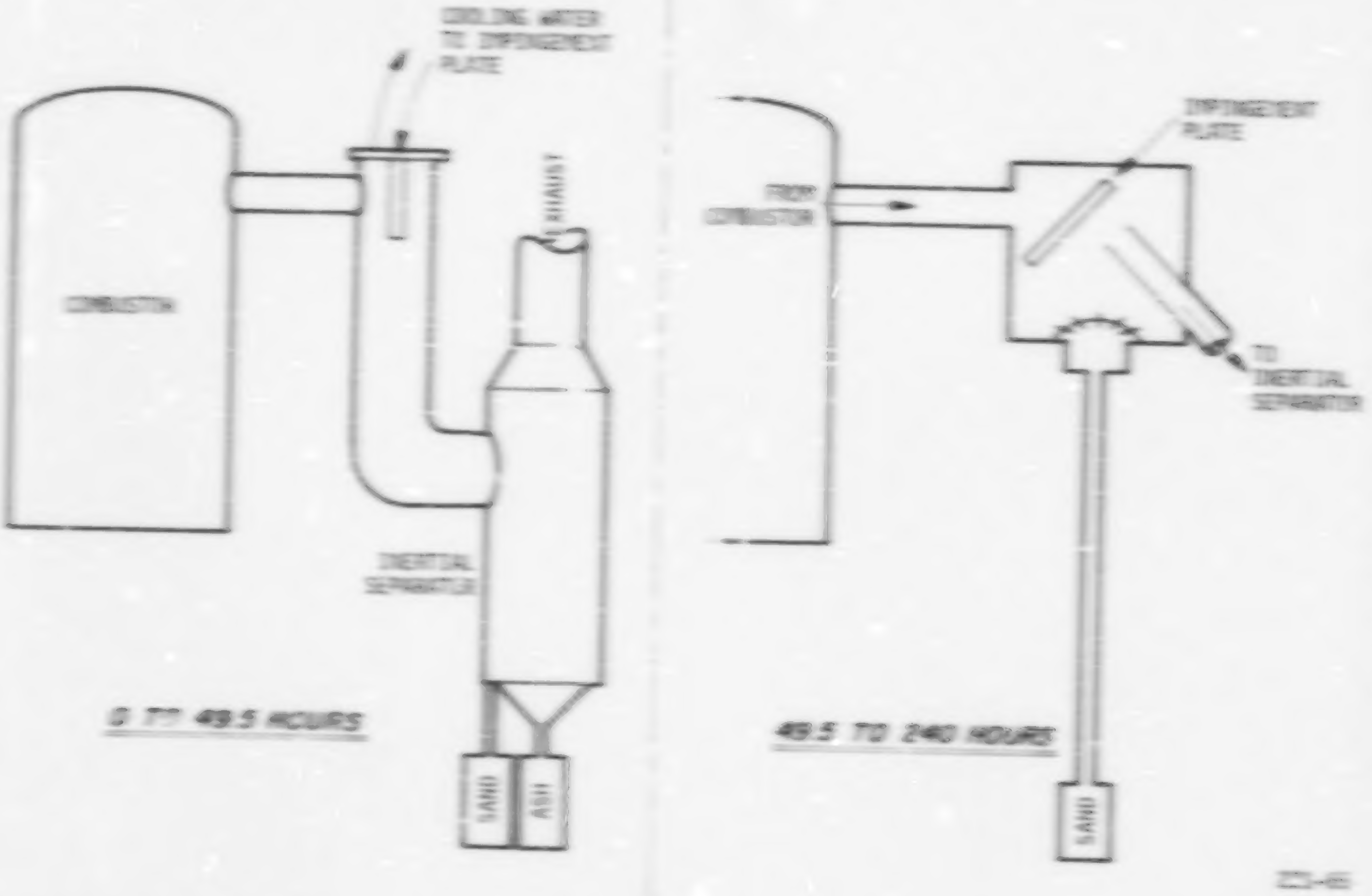

COOLING WATER
TO IMPINGEMENT
PLATE
COMBUSTOR
EXHAUST
INERTIAL
SEPARATOR
0 TO 49.5 HOURS
SAND
ASH
FROM
COMBUSTOR
IMPINGEMENT
PLATE
TO
INERTIAL
SEPARATOR
49.5 TO 240 HOURS
SAND
221-65

Figure 3-57 Exhaust Gas Impingement Plate Configuration

7 percent was deposited downstream in the exhaust and inertial separator.

Mass Accounting-

A summary of the materials handled during the 240 hour test is shown in Table 3-16. Except for those noted as having been calculated, all weights cited in the table were taken from a beam balance scale. The solid waste ash content was calculated from incinerator refuse and residue data presented during the 1968 National Incinerator Conference[4] and was adjusted for moisture and inerts content. The flyash entrained in the exhaust gas was calculated from particle loading data. Table 3-16 shows that the total amount of calculated inerts added (including ash) was 5111 pounds. The measured inerts and ash weighed 5846 pounds. This is a discrepancy of 12.6 percent and is probably the result of a nonrepresentative solid waste inert content value. This value is suspect because of the excessive handling required in model combustor operation. This causes the inert fraction to settle in the storage vessels, and results in a nonrepresentative grab sample. The measured inerts plus ash percent of 5846/32074 x 100 = 18.25 percent (of which one-third is ash), is in accord with previous findings. Table 3-16 also shows that 1977 pounds of ash, (defined as all particulates smaller than 100 mesh) passed through the sand separator, and that 3787 pounds of sand were removed from the bed and sand separator.

Table 3-16. LP-5 SOLIDS MASS ACCOUNTING

Parameter	0 - 120 hrs	120 - 240 hrs	Total
Solid waste consumed (lb)	15,599	16,479	
Ash content (lb)	990 @ 6.35%[a]	1054 @ 6.40%[a]	2,044
Feed rate (lb/min)	2.16	2.18	
Average moisture (%)	20.9	26.2	
Average inerts (%)	11.27	8.04	
Total inerts (lb calculated)	1,758	1,309	3,067
Total (ash & inerts)			5,111
Bed sand removed (lb)	339	925	1,264
Sand exhausted from combustor (lb)	1,208	1,315	2,523
Flyash exhausted from combustor (lb)	1,263 (380)[b]	714 (205)[b]	1,977
Hard clinker formation (lb)	42	40	82
Total	2,852	3,199	5,846

[a] Ash content is defined as particulates smaller than 100 mesh.

[b] The number in parentheses represents the ash penetrating the inertial separator. The values are based on particle loading measurements.

Development of the Residue Removal System

During the LP-8 test series, it was found that the inerts inflow to the vertical combustor equaled the bed material elutriation and, therefore, no bed material removal was required. The data obtained from the model testing indicated that a significant amount of metal should accumulate during pilot plant operation; but actual operation of the vertical combustor in excess of 100 hours yielded metal levels of 0.5 percent - significantly below the anticipated steady state metal level of 10 percent. This large difference in metal content was thought to be associated with improvements in solid waste shredding/air classifying equipment used during the LP-8 testing. The steady state level was determined by using a metal attrition rate of 0.004 pounds per hour per pound of metal present, a 0.16 percent content of high melting point metal in the solid waste feed, and a flow rate of 30 pounds per minute.

However, it was determined that a material removal system would be needed for the first stage separator. The primary function of this device was to remove sticky particles and the larger inerts from the gas stream. The sticky particles, such as molten aluminum, are deposited and are converted to aluminum oxide in the spinner duct of this vessel. The inert materials elutriating from the combustor provide the scrubbing action necessary to eliminate any significant buildup of material. The material accumulating in the bottom of this separator (sand, flaked deposits, ash, etc.) must be continually removed or it will fuse into a large clinker. This occurred when material was allowed to accumulate in the bottom of the pilot plant first stage separator during a 24-hour test. The material removal system developed to alleviate this problem is shown in Figure 3-58 and was first used during the LP-11 testing.

During the LP-11 testing, the material removal system was operated for approximately 100 hours and successfully demonstrated the continuous removal of the residue material and its transportation to an external collection point. The sand/ash mixture was pneumatically transported to a sand bin through a 2-inch diameter pipe. The fines were pneumatically transported and collected in the existing medium temperature baghouse system. The flow limiter plate at the end of the pipe in the sand bin was used to control and to adjust the gas flow rate in the transport pipe.

A similar setup will be used for direct fluid bed combustor material removal during future high pressure operations if the bed depth does not stabilize at a suitable level. However, minor modifications will be made to the system to permit residue unloading during high pressure operation. These modifications consist of the incorporation of a double-ball valve air-lock volume with continuous bleed in the pipe section below the vessel outlet, and the removal of the transport line ball valve. The double-ball valve arrangement with intermediate volume bleed will allow cyclic unloading from the pressurized system without exposing the ball valves to high velocity conditions.

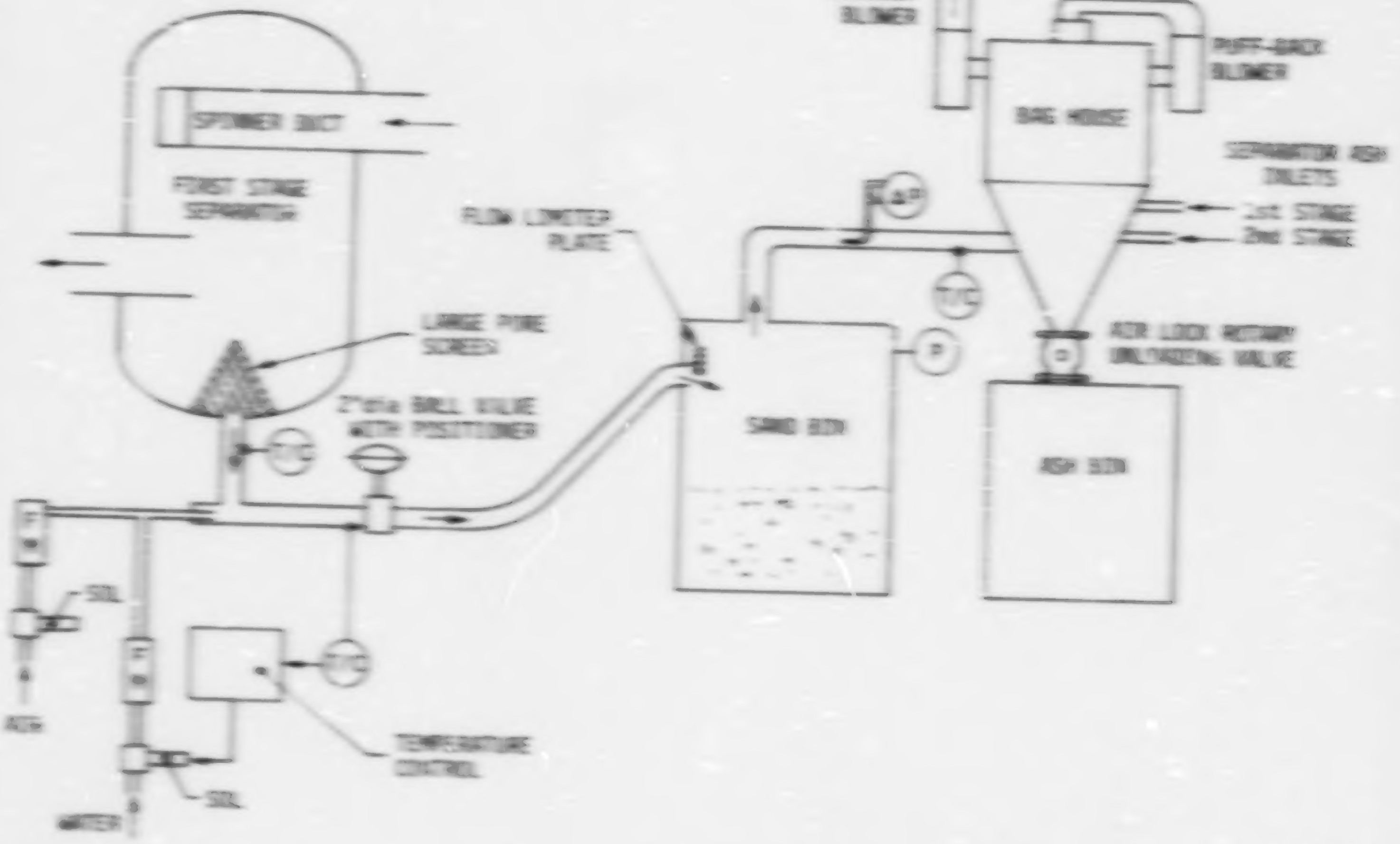

SPINNER DUCT
FIRST STAGE SEPARATOR
LARGE PORE SCREEN
T/C
2"dia BALL VALVE WITH POSITIONER
FM
SOL
AIR
FM
SOL
WATER
T/C
TEMPERATURE CONTROL
FLOW LIMITER PLATE
SAND BOX
ΔP
T/C
P
EXHAUST BLOWER
BAG HOUSE
PUFF-BACK BLOWER
SEPARATOR ASH INLETS
1st STAGE
2nd STAGE
AIR LOCK ROTARY UNLOADING VALVE
ASH BIN
221-221

Figure 3-58 Material Removal System Schematic - Low Pressure Operation

The pipes above and below the valves will be water-jacketed to facilitate cooling. The ash removal and residue removal system that will be integrated into the pilot plant for high pressure testing is shown in Figure 3-59.

DETERMINATION OF OFF-GAS COMPOSITION OF A FLUID BED COMBUSTOR FUELED WITH MUNICIPAL SOLID WASTE (TASK PL-3)

Testing was conducted to establish the chemical qualitative and quantitative composition of the off-gases and fumes from a fluid bed combustor burning municipal solid waste. The purpose of the testing was to establish the principal corrosive constituents of gases and flyash particulates and their concentrations to permit simulation of the fluid bed exhaust during the turbine blade corrosion/deposition testing which was later conducted by The Westinghouse Research Laboratories. The gas analysis testing consisted of operating a fluid bed combustor with municipal solid waste fuel utilizing parallel exhaust analysis methods. One method was a continuous on-line sampling of the exhaust for gas composition with a mass spectrometer. The other method consisted of two identical sequences of collecting gas samples and particulate samples utilizing standard dry and wet chemistry methods developed for pollution analysis. Repetition of the sample collection sequence was scheduled for protection against possible sample loss or contamination during the analysis.

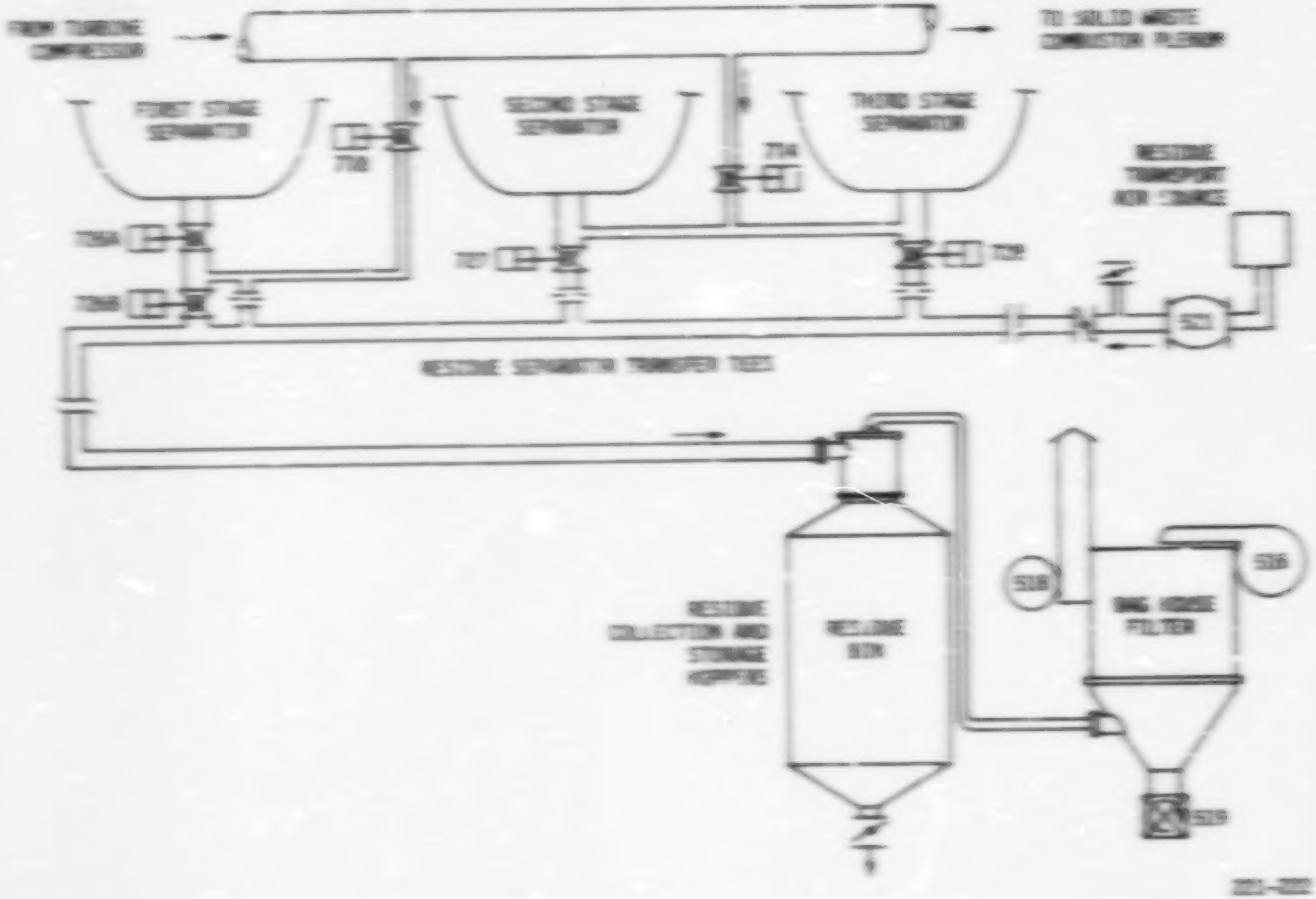

FROM TURBINE COMPRESSOR
TO SOLID WASTE COMBUSTOR PLENUM
FIRST STAGE SEPARATOR
SECOND STAGE SEPARATOR
THIRD STAGE SEPARATOR
718
714
727
RESIDUE TRANSPORT AIR SOURCE
521
RESIDUE SEPARATOR TRANSFER TEES
RESIDUE COLLECTION AND STORAGE HOPPERS
RESIDUE BIN
BAG HOUSE FILTER
518
516
519

Figure 3-59 Pilot Plant Material Removal System

Test Setup for Determination of Off-Gas Composition

Testing was performed using the CPC-designed Model No. 1 fluid bed combustor in the test setup shown in Figures 3-60 and 3-61. The Model No. 1 combustor, a 1-foot by 2-foot low pressure fluid bed combustor, burning shredded and air classified municipal solid waste, was used to generate the off-gases and flyash particulates. The combustor was operated at 1400° F with the off-gases at a nominal 1600° F in the exhaust duct. The fluid bed was 16 mesh silica sand, the static sand height 2 feet, and the superficial velocity 5.2 ft/sec. No techniques nor additives were added to suppress any constituent of the exhaust gas.

The exhaust gas sample was collected downstream from a modified Donaldson Company inertial separator. The sample collection and distribution system is shown schematically in Figure 3-62. The sampling system was constructed from 300 series stainless steel components and was designed for continuous gas sampling with the mass spectrograph, gas sample collection for later laboratory analysis, and for primary particulate collection with an in-line filter. A secondary particle collection point was incorporated into the overboard vent of the residue collection tank below the inertial separator assembly.

Gas Analyses

The wet sampling and chemical analyses were conducted by the Trapelo-West Laboratories, Inc. The continuous on-line gas sampling was performed by Uthe Technology, Inc., using a Uthe quadropole mass spectrometer type of gas analyzer. The laboratory results of the gas

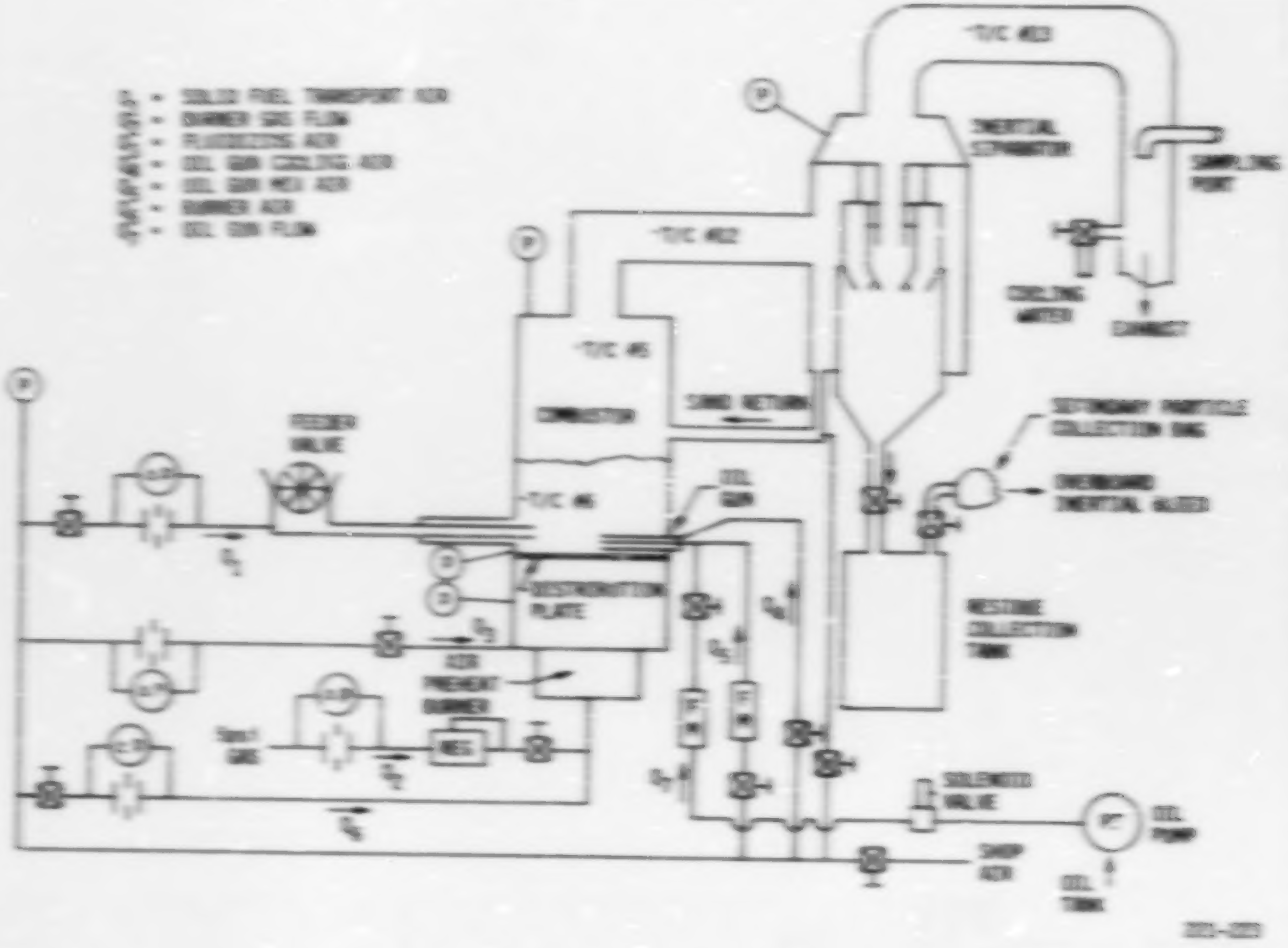

Q_1 = SOLIDS FUEL TRANSPORT AIR
Q_2 = BURNER GAS FLOW
Q_3 = FLUIDIZING AIR
Q_4 = OIL GUN COOLING AIR
Q_5 = OIL GUN MIX AIR
Q_6 = BURNER AIR
Q_7 = OIL GUN FLOW
P
T/C #3
INERTIAL SEPARATOR
SAMPLING PORT
T/C #2
COOLING WATER
EXHAUST
T/C #5
COMBUSTOR
SAND RETURN
SECONDARY PARTICLE COLLECTION BAG
OVERBOARD INERTIAL BLEED
FEEDER VALVE
T/C #6
OIL GUN
DISTRIBUTION PLATE
RESIDUE COLLECTION TANK
Q_1
Q_3
Q_4
Q_5
AIR PREHEAT BURNER
Test GAS
REG
Q_2
Q_6
Q_7
SOLENOID VALVE
OIL PUMP
SHOP AIR
OIL TANK
221-223

Figure 3-60 Test Apparatus Schematic

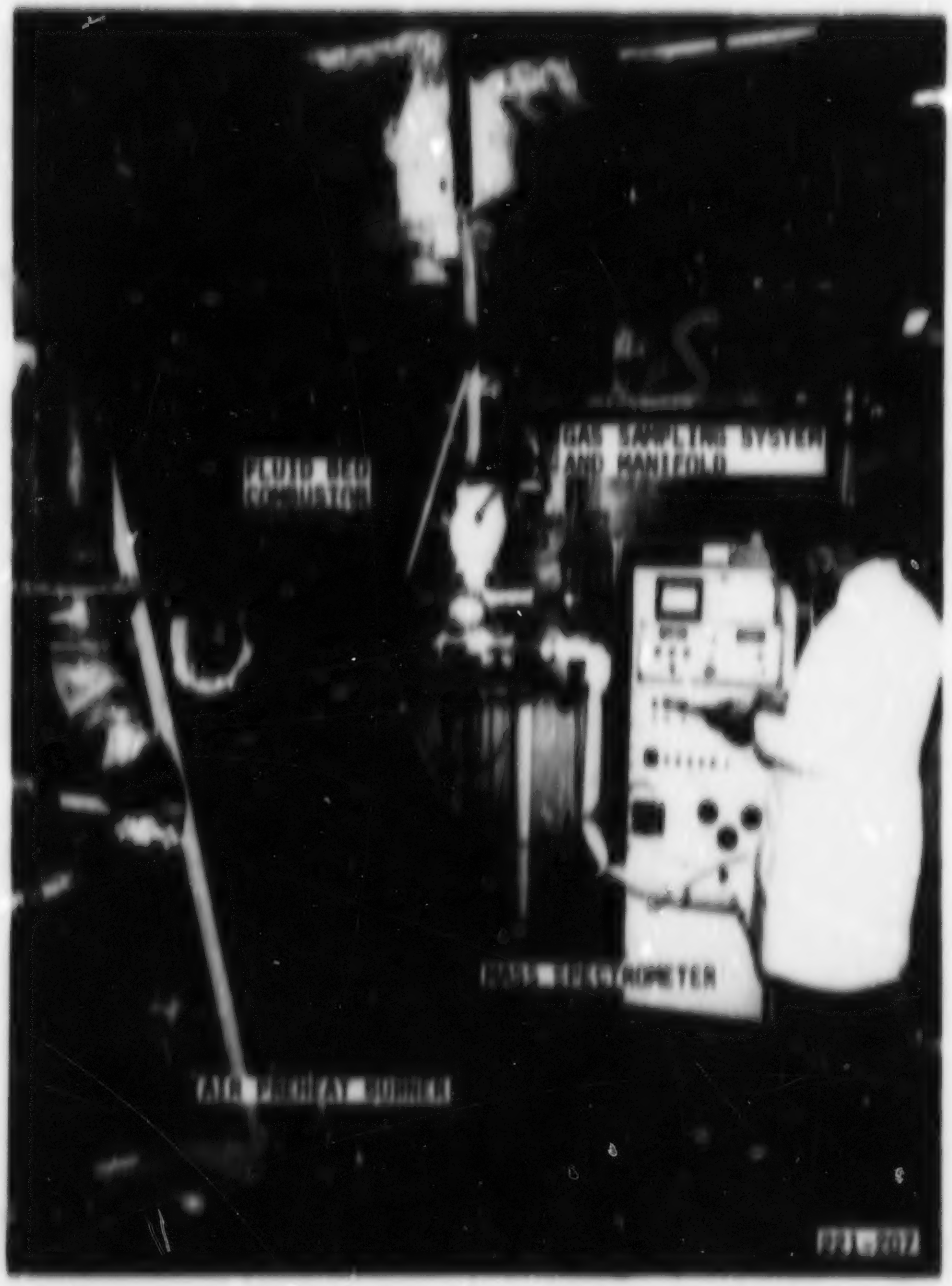

FLUID BED
COMBUSTOR
GAS SAMPLING SYSTEM
AND MANIFOLD
MASS SPECTROMETER
AIR PREHEAT BURNER

Figure 3-61 Test Apparatus

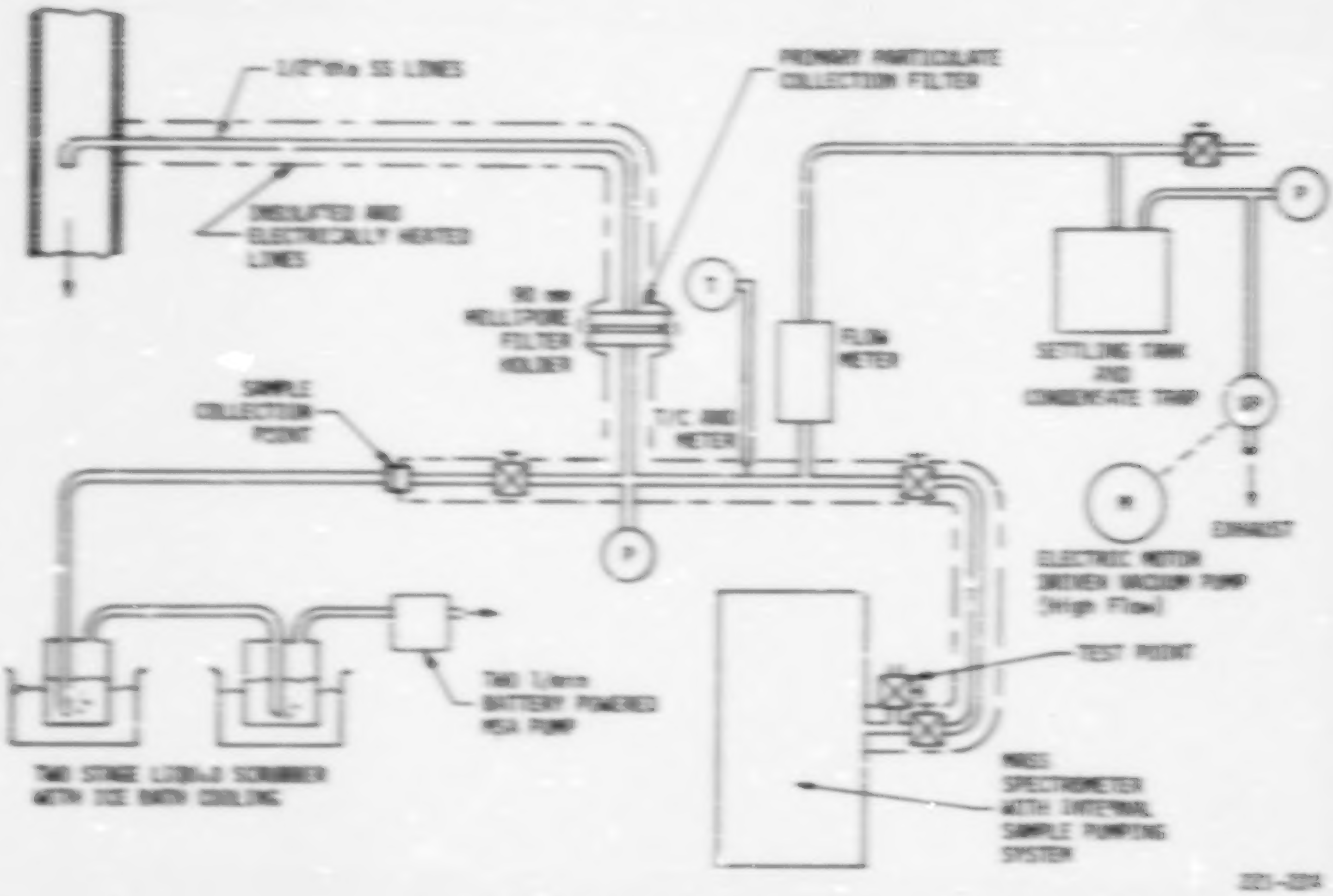

1/2"dia SS LINES
INSULATED AND ELECTRICALLY HEATED LINES
PRIMARY PARTICULATE COLLECTION FILTER
90 mm MILLIPORE FILTER HOLDER
T
T/C AND METER
FLOW METER
P
SETTLING TANK AND CONDENSATE TRAP
VP
M
EXHAUST
ELECTRIC MOTOR DRIVEN VACUUM PUMP (High Flow)
SAMPLE COLLECTION POINT
TEST POINT
MASS SPECTROMETER WITH INTERNAL SAMPLE PUMPING SYSTEM
TWO 1/min BATTERY POWERED MSA PUMP
TWO STAGE LIQUID SCRUBBER WITH ICE BATH COOLING
221-224

Figure 3-62 Sample Collecting System

analyses are summarized in Table 3-17. The techniques used in obtaining the data are described in Appendix B.

As shown in Table 3-17, the analytical results reveal six major constituents for the combustor off-gas, namely nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and water vapor (H_2O). All other constituents appear in such small quantities that their concentration can better be expressed in parts per million (ppm) units rather than in percentages. The amounts of N_2, O_2, CO_2, and H_2 are typical for combustion exhaust gas while the concentrations of unburned hydrocarbons and CO are unusually high and low, respectively. The low levels of nitrogen oxides (NO_x) and high unburned hydrocarbon levels obtained under the 300 percent excess oxygen conditions were surprising when compared to available literature on solid waste incineration. Later tests gave repeated NO_x concentrations between 100 and 200 ppm and HC less than 20 ppm.

Particle Analyses

The flyash collected at the exit of the inertial separator residue collection tank (the secondary particulate collection point) was analyzed by the Trapelo-West Laboratory as well as by another outside laboratory, the Metallurgical Labs., Inc. of San Francisco. Trapelo-West determined the anions chloride (Cl^-), fluoride (F^-), sulfate (SO_4^{-2}), and phosphorus pentoxide ($P_2O_5^-$), and also ran emission spectroscopic analyses for the primary and secondary particulate collection. Metallurgical Labs., Inc. determined the anions and concentration of the major constituents of the flyash from the secondary particulate collection point by wet chemical

Table 3-17. ANALYTICAL RESULTS OF COMBUSTOR EXHAUST GAS ANALYSIS

Gas		Trapelo data	Converted data (%)	Corrected data for gas composition
CO_2	#1	5.4%		4.9%
	#2	5.7%		5.45%
CO	#1	0.2%		0.18%
	#2	0.2%		0.19%
O_2	#1	14.0%		12.8%
	#2	15.5%		14.8%
N_2	#1	80.4%		73.6%
	#2	78.6%		75.1%
NO_x	#1	0.5 mg/m³	0.00004	0.4 ppm
	#2	0.5 "	0.00004	
NO	#1	0.6 mg/m³	0.00005	0.5 ppm
	#2	0.5 "	0.00004	0.4 ppm
NO_2	#1	0.1 mg/m³	0.000008	0.08 ppm
	#2	0.1 "	0.000008	0.08 ppm
SO_x	#1	22 mg/m³	0.0018	18 ppm
	#2	10 "	0.0008	8 ppm
HCl	#1	84 mg/m³	0.0067	67 ppm
	#2	114 "	0.0091	91 ppm
HF	#1	<0.01 mg/m³	0.000001	<0.01 ppm
	#2	<0.01 "	0.000001	<0.01 ppm
NH_3	#1	<0.05 mg/m³	0.000004	<0.04 ppm
	#2	<0.05 "	0.000004	<0.04 ppm
H_2S	#1	<1.0 mg/m³	0.00008	<0.8 ppm
	#2	<1.0 "	0.00008	<0.8 "
P_2O_5	#1	1.0 mg/m³	0.00008	0.8 ppm
	#2	0.1 "	0.000008	0.08 ppm
CH_4	#1	<1 ppm	0.0001	<1 ppm
	#2	<1 ppm	0.0001	<1 ppm
HC	#1	5.9%		5.9%
	#2	2.4%		2.4%
H_2	#1	<1 ppm	0.0001	<1 ppm
	#2	<1 ppm	0.0001	<1 ppm
H_2O	#1	33 mL/m³	2.6	2.6
	#2	25 "	2.0	2.0

methods while the minor constituents were derived from an emission spectrum. The results of the flyash analyses are summarized in Table 3-18. It must be noted that the percentages listed are converted values for metals oxides. The techniques used in obtaining the flyash analyses data are described in Appendix B.

Turbine Blade Material Testing

The results of the analyses of the combustor exhaust gas and flyash were forwarded to the Westinghouse Research Laboratories for use in the turbine blade material testing. These tests were conducted by the Westinghouse Research Laboratories, Combustion Systems Research Group under EPA Contract 68-03-0049.[5] The tests were conducted with a turbine simulator operating under the pressure and temperature conditions expected for the candidate turbines being considered for use with the CPU-400 systems. The blade material investigated included samples of the types of metals used in the CPU-400 pilot plant turbine, (the Ruston TA-1500), and samples of the types of metals used in the blades of the CPU-400 prototype candidate turbines - the newer Westinghouse and General Electric turbines.

The test results showed no attack other than oxidation, i.e., no sulfidation or "hot corrosion". Oxide scales were left intact even though the deposit spalled, and no localized attack was found other than the normal penetration of oxide at grain boundaries in spite of the presence of chlorine, sulfur, and alkali metals in the test environment. Conservative extrapolation of the data indicated that a machine life in excess of 10,000 hours should be obtainable.

Table 3-18 FLYASH ANALYSIS SUMMARY

	Trapelo-West Labs, Inc.		Metallurgical Labs, Inc. (secondary flyash collection point)	
Component	Primary flyash collection point	Secondary flyash collection point	Wet chem. determ	Emission spect.
SiO_2	48.0	35.0	42.96	Major
Al_2O_3	19.0	19.0	26.95	Major
CaO	14.0	14.0	10.64	10.0
Fe_2O_3	2.4	2.0	5.08	5.0
Na_2O	6.7	11.3	5.08	4.0
K_2O	2.4	4.6	2.96	2.4
MgO	3.4	3.4	2.02	3.0
TiO_2	1.3	1.3		1.3
PbO_2	0.1	2.0		0.25
SnO_2	0.1	0.35		0.1
ZnO	0.7	0.70		0.5
CoO	0.001	0.001		0.002
Mn_2O_3	0.4	0.25		0.1
MoO_3	0.01	0.01		0.01
Ag_2O	0.001	0.001		0.001
V_2O_5	0.008	0.008		0.009
SrO	0.02	0.02		0.02
ZrO_2	0.01	0.01		0.01
B_2O_3	0.02	0.02		0.02
BaO	0.4	0.4		0.3
CuO	0.05	0.05		0.07
NiO	0.06	0.04		0.09
Cr_2O_3	0.20	0.20		0.09
P_2O_5	2.2	2.2	2.31	0.6
SO_4			5.24	
Cl			0.11	
F			0.0016	

[a] All values are expressed in percent

[illegible]

SECTION IV

CONTROLS AND INSTRUMENTATION

Controls and instrumentation were designed and developed to support the 24- and 48-hour test runs defined in tasks LP-8 and LP-11. The controls and instrumentation used to support the 2-hour test run defined in task LP-1 were designed under a previous contract.

Task LP-8 specified 6 hours of continuous system operation in an exhaust temperature within ± 20° F of a selected setpoint and 18 hours of continuous system operation in an exhaust temperature band within ±30° F of the selected setpoint. To achieve this requirement, an analog (semi-automatic) type control system was developed.

Task LP-11 specified 48 hours of continuous pilot plant operation in a fully automatic control environment. During this period the exhaust temperature variance was to be maintained within ± 10° F of a selected setpoint for 36 hours and ± 30° F for 12 hours, or the exhaust temperature variance could be maintained within ± 20° F of the selected setpoint for the entire 48 hours. A computerized (automatic) control system was designed and developed to support this task and the future task requirements of high pressure turbine testing. The design of this control system was authorized under task LP-9. Its procurement, fabrication, installation, and checkout were accomplished under task LP-10.

In addition to the above, various gas analysis equipment and techniques were developed to sample and analyze the combustor off-gas constituents.

DESIGN AND DEVELOPMENT OF GAS ANALYSIS EQUIPMENT

Off-gas constituents selected for continuous analysis were limited to those whose presence could cause adverse health effects, or whose determination were useful for the study of combustion efficiency as well as corrosion problems within the pilot plant system. The exhaust gas compounds selected for gas composition analyses were: oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), oxides of nitrogen (NO_x) sulphur dioxide (SO_2), and hydrogen chloride (HCL).

Gas Composition System

The on-line gas analysis system developed for this program consisted of two infrared analyzers for CO and CO_2, a flame ionization detector for hydrocarbons, two electrochemical reaction cells for NO_x and SO_2, and one polarographic analyzer for oxygen. These instruments are installed into a mobile cabinet rack as shown in Figure 4-1. A schematic of the on-line gas analyzer system is shown in Figure 4-2. A description of the gas analysis equipment is presented in Appendix C.

An off-line titration technique was developed for determination of the HCl level in the exhaust gas. A volume of the exhaust gas was first bubbled through a solution of sodium hydroxide. The liquid was then analyzed in the laboratory for the concentration of sodium chloride. An attempt was made to procure an on-line instrument for HCl measurement using a gas chromatograph. However, after trying a number of different columns and packing materials, it was determined by the instrument subcontractors that it was beyond the present state of the art. The main problem in this endeavor was the high moisture level in the

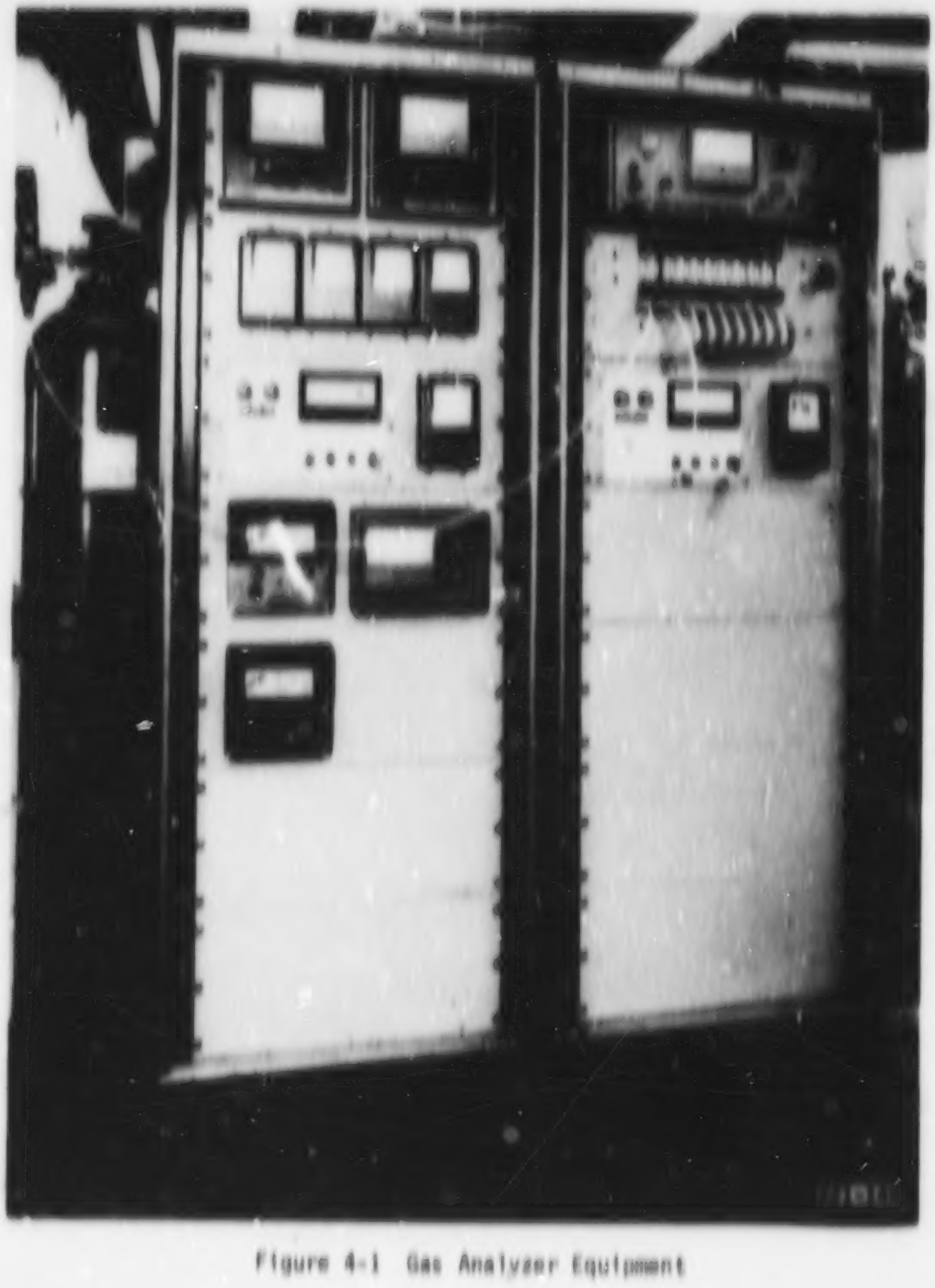


Figure 4-1 Gas Analyzer Equipment

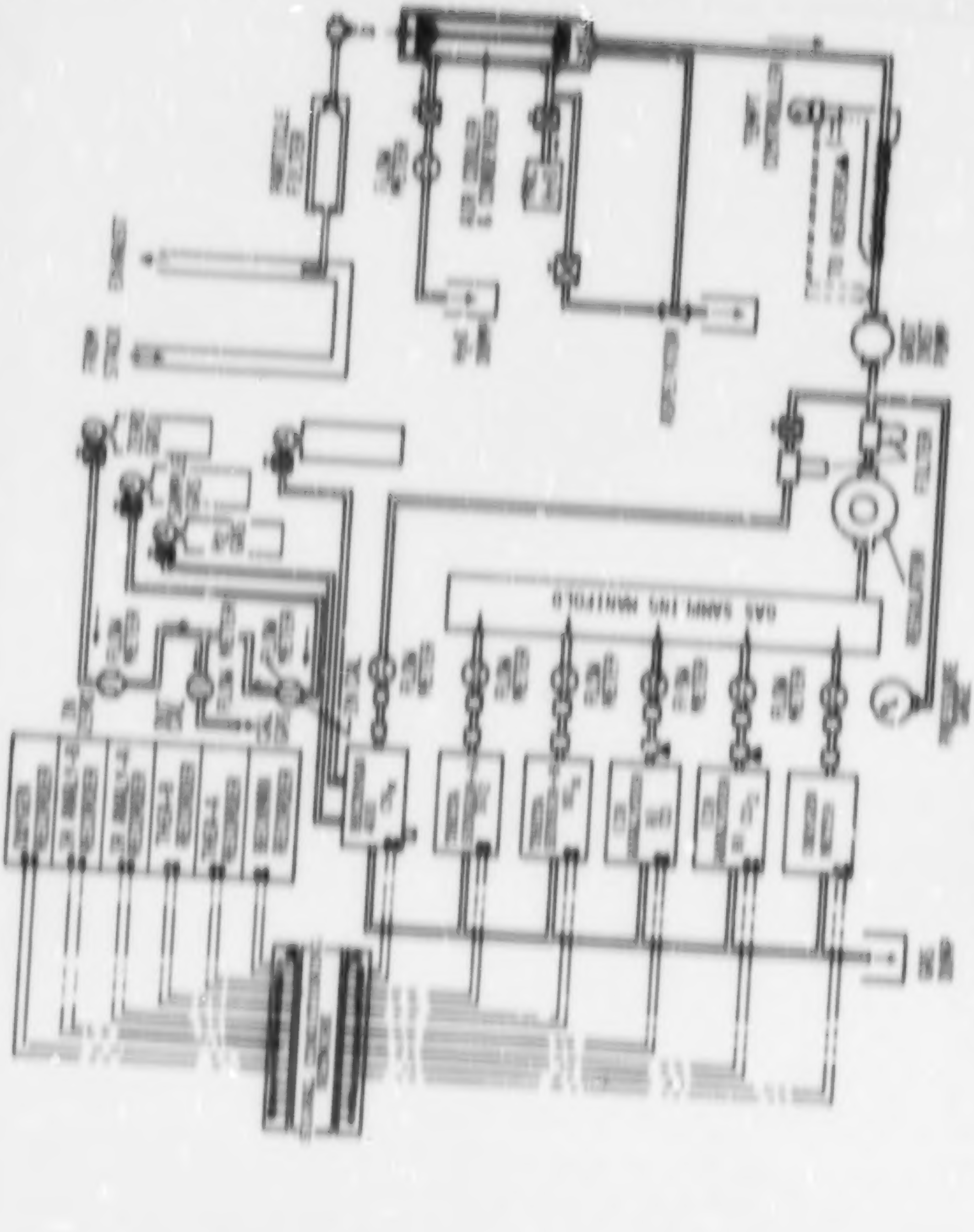

GAS SAMPLING MANIFOLD

Figure 4-2 On-line Gas Analysis System Schematic

exhaust gas along with the relatively low levels of HCl that had to be measured (150 ppm). The water tended to interfere with and mask the HCl reading.

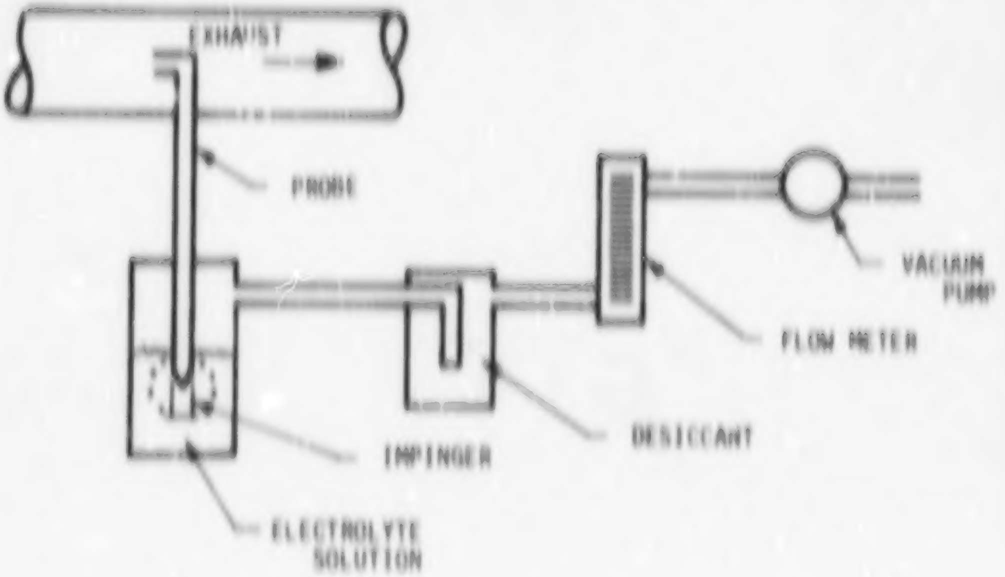
Particle Analysis

The off-line particle analysis technique used for this test program is shown schematically in Figure 4-3. Particles were taken at 2 to 5 hour intervals, and were collected in a special electrolytic solution using an impinger. Following the collection, the wet sample was analyzed in the laboratory for the particle count versus particle size, using a Coulter Model Z analyzer (Figure 4-4). The analyzer determined particle sizes by passing a current through a calibrated orifice in the particle-laden electrolyte, forcing a measured quantity of fluid through the orifice, and measuring the change in resistance caused by liquid borne particles flowing through the orifice and correlating the change in resistance to particle size. The particle sampling and analysis technique is discussed in Appendix C.

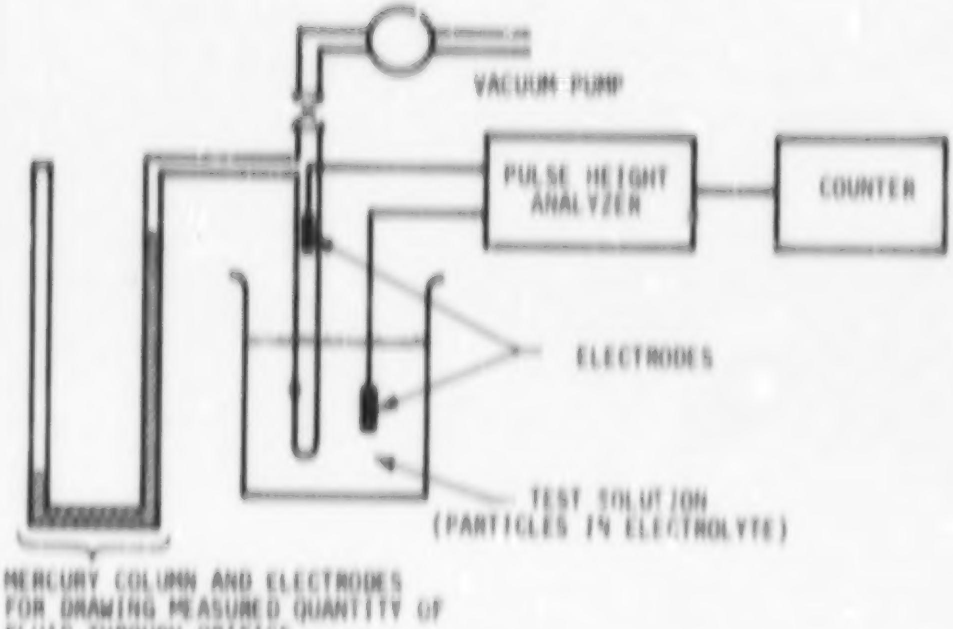
Testing

One significant problem encountered during testing with the gas analysis equipment has been the attenuation of SO_2 in the sampling system due to water condensation. Wet chemistry backup samples were used to determine attenuation levels and their changes. However, no consistent data were obtained to allow correction for SO_2 loss in the system.

The results of the gas composition and particle analyses performed during the LP-8 and LP-11 tests are summarized in Section V.


EXHAUST
PROBE
VACUUM PUMP
FLOW METER
DESICCANT
IMPINGER
ELECTROLYTE SOLUTION

SAMPLE COLLECTION


VACUUM PUMP
PULSE HEIGHT ANALYZER
COUNTER
ELECTRODES
TEST SOLUTION (PARTICLES IN ELECTROLYTE)
MERCURY COLUMN AND ELECTRODES FOR DRAWING MEASURED QUANTITY OF FLUID THROUGH ORIFICE

SAMPLE ANALYSIS

221-161

Figure 4-3 Particle Analysis, Off-line Technique

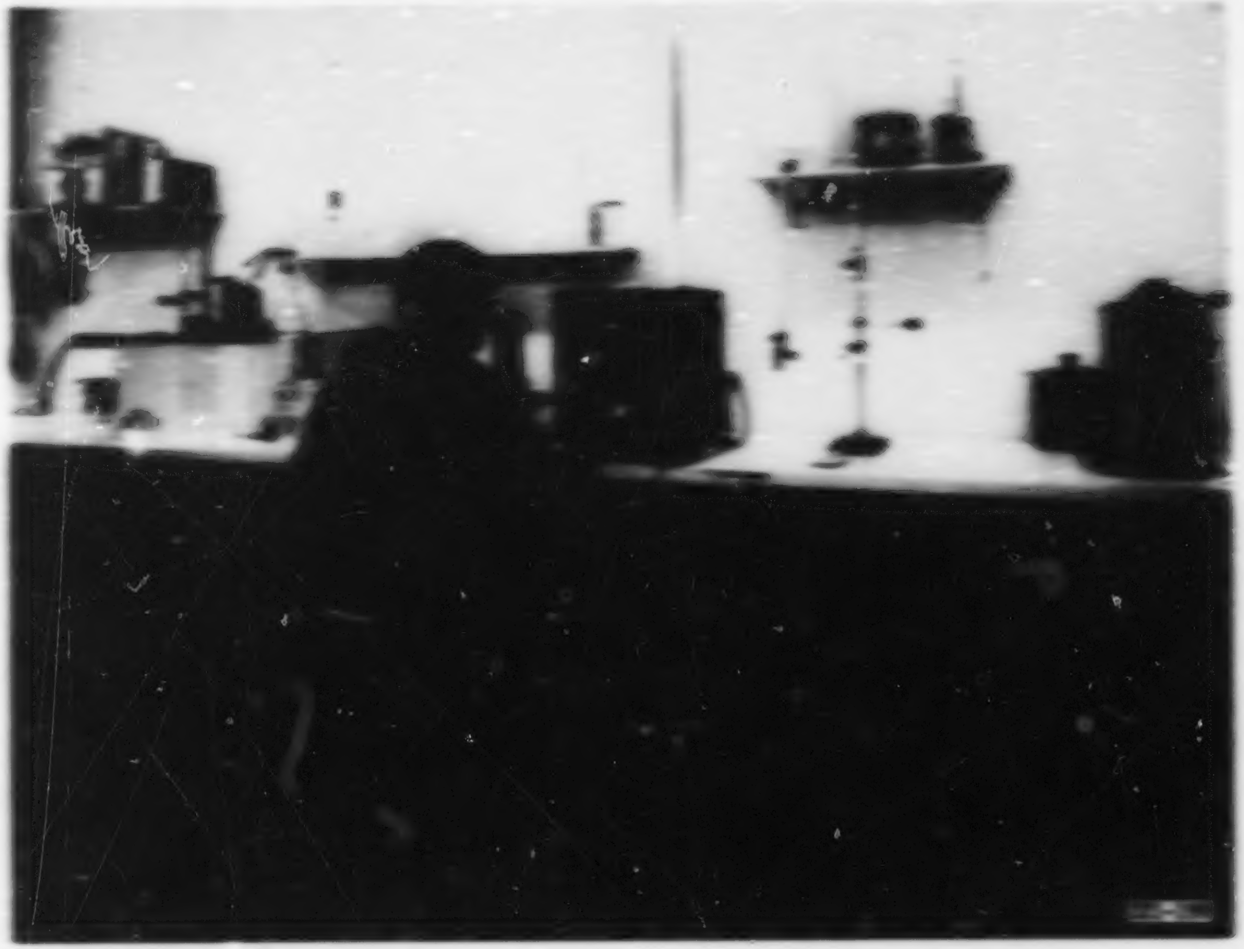


Figure 4-4 Coulter Z Analyzer

DESIGN AND DEVELOPMENT OF SEMIAUTOMATIC CONTROLS AND INSTRUMENTATION

The semiautomatic control system was designed to maintain the hot gas subsystem operating at a steady state level. Operator intervention is required only to perform various system checks prior to operation and to change levels or operating configurations. This control configuration was used as the primary pilot plant control medium during the LP-8 testing series and served as a backup control source during the LP-11 testing series.

Location of Controls

The semiautomatic control system controls were located in a centrally situated control room (Figure 4-5) adjacent to the pilot plant. The following paragraphs describe the primary control loops used in the semi-automatic control configuration. Simplified block diagrams of the pilot plant control loops are presented in Section V.

Gas Temperature Control

Originally, during LP-1 testing it was planned to utilize two primary control loops to control the gas temperature. The first primary control loop was to have been a high response loop controlling gas temperature through control of a mixing air flow (a bypass flow around the combustor which would be equivalent to a bypass air loop in a turbine system). The second primary control loop was to have been a low response loop controlling the combustor temperature through control of the solid waste feed rate. Short term variations in the gas outlet temperature were to

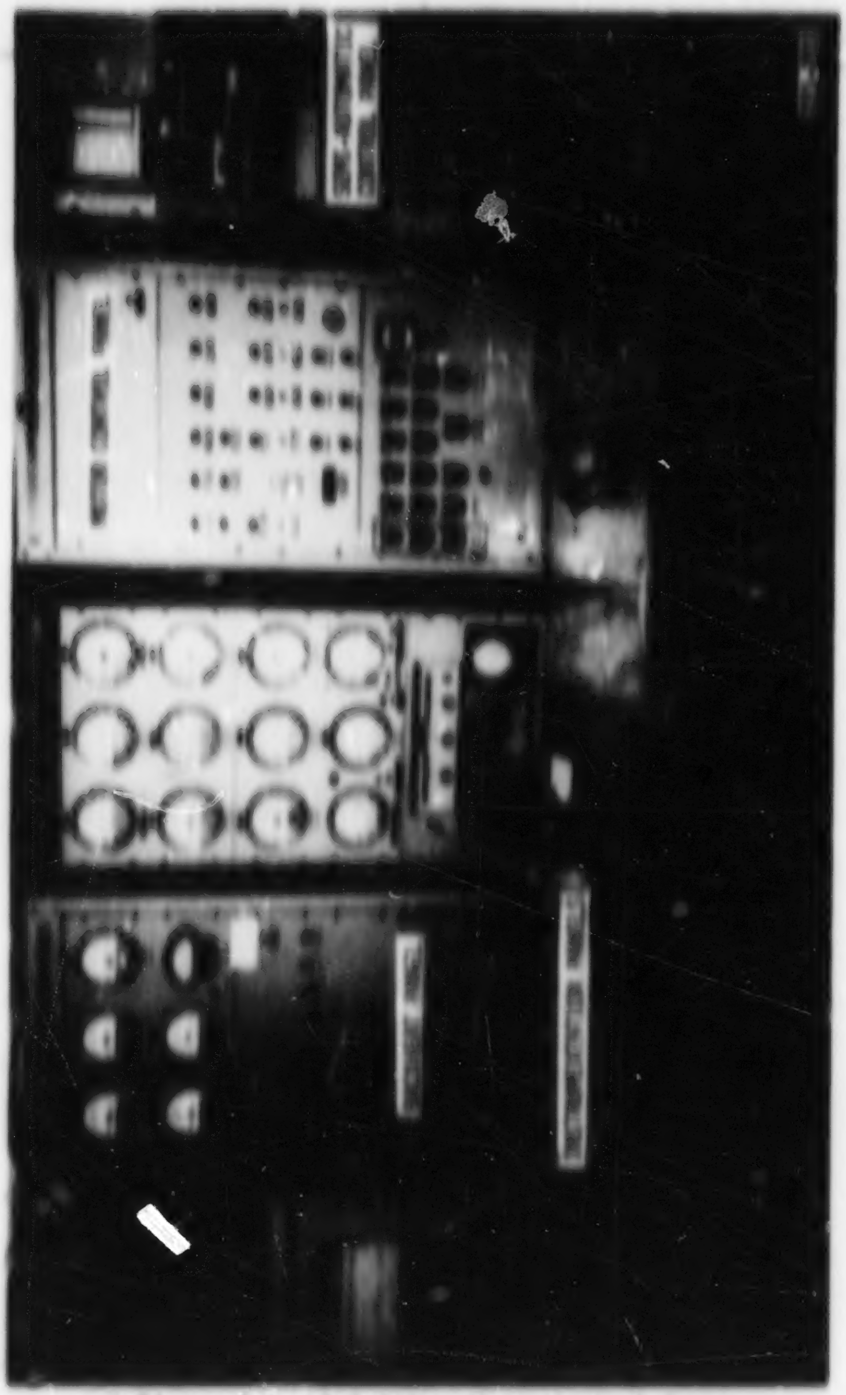
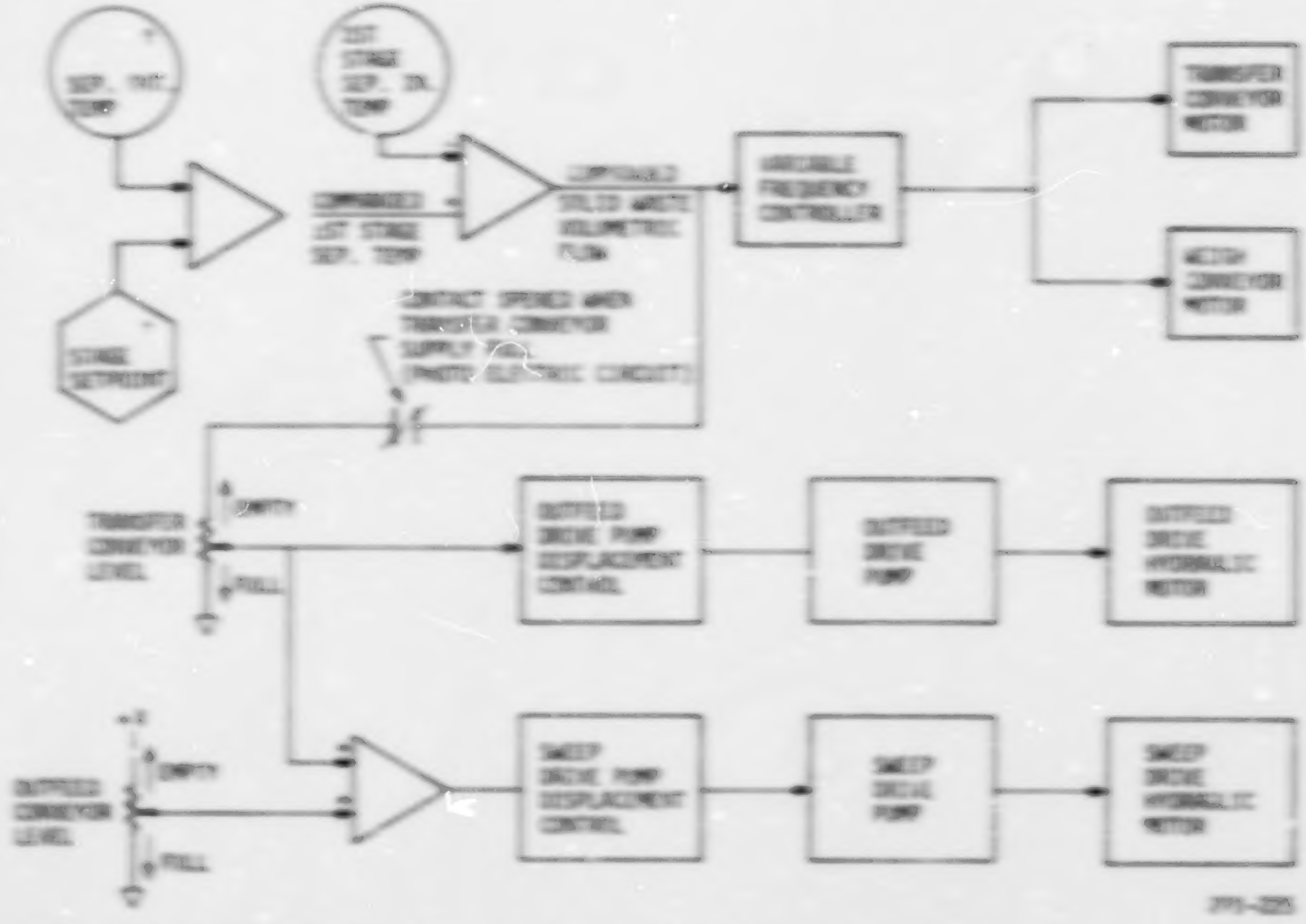


Figure 4-5 LP-8 Pilot Plant Control Room

have been damped by the thermal inertia of the first and second stage separators.

However, preliminary testing of this control scheme uncovered a basic stability problem in that the bypass air control tended to couple with the combustion process as a result of the change in the fluidizing air flow. It has been assumed that the bed would tend to absorb or attenuate the effect of any unbalance in energy between solid waste input and hot gas output, but, instead of the bed acting as a thermal inertia, the increase in bypass air (reduced fluidizing air flow) resulted in increased afterburning, thereby offsetting the temperature reduction which the increased bypass air flow was to provide.

The gas temperature control scheme for the pilot plant eventually evolved as a single cascaded loop, shown in Figure 4-6. The inner loop measured the gas temperature in the top of the first stage separator, compared this temperature to a setpoint or commanded temperature, and then adjusted the commanded solid waste flow rate to correct any errors. The gas temperature at the top of the first stage separator was used because it proved to be the highest temperature in the system, thereby being the most representative of the combustion process. In the outer loop the second stage separator (LP-8), or third stage separator (LP-11) outlet temperature was used as the controlled parameter. Any deviation in this temperature from an operator selected setpoint would cause a change in the commanded first stage separator top temperature, which, in turn, would cause a change in the commanded solid waste flow rate. The inner loop provided the means to respond rapidly to variations in the solid


SEP. OUT. TEMP
*
STAGE SETPOINT
*
1ST STAGE SEP. IN. TEMP
COMMANDED 1ST STAGE SEP. TEMP
COMMANDED SOLID WASTE VOLUMETRIC FLOW
VARIABLE FREQUENCY CONTROLLER
TRANSFER CONVEYOR MOTOR
WEIGH CONVEYOR MOTOR
CONTACT OPENED WHEN TRANSFER CONVEYOR SUPPLY FULL (PHOTO-ELECTRIC CIRCUIT)
TRANSFER CONVEYOR LEVEL
EMPTY
FULL
OUTFEED DRIVE PUMP DISPLACEMENT CONTROL
OUTFEED DRIVE PUMP
OUTFEED DRIVE HYDRAULIC MOTOR
OUTFEED CONVEYOR LEVEL
EMPTY
FULL
SWEEP DRIVE PUMP DISPLACEMENT CONTROL
SWEEP DRIVE PUMP
SWEEP DRIVE HYDRAULIC MOTOR
771-225

* SECOND STAGE SEPARATOR FOR LP-8; THIRD STAGE SEPARATOR FOR LP-11

Figure 4-6 Gas Temperature Control Loop (LP-8 and LP-11)

waste makeup, or feed system. The outer loop was a relatively slow responding loop which provided the fine tuning of the system to maintain the outlet temperature at the desired level.

Feedline Air Flow Control

Secondary control loops (Figure 4-7) were used to control feed line air flow rate in the two solid waste feed lines to the combustor. These loops utilized a pitot tube differential pressure measurement (corresponding to an air flow rate) as the controlled parameter and variable position throttling valves in the feed lines as the controlled units.

Dump Air and Combustor Air Control

Additional control loops (Figure 4-8) were initially incorporated to control the dump air flow rate (via valve 005) and the plenum inlet flow (via valve 012) based on pressure measurements. However, problems were encountered in obtaining a meaningful flow measurement, and it was also established that the position of these valves did not have to be adjusted once a stable condition had been reached. Therefore, these additional control loops were eliminated and the valve positions were subsequently controlled directly by the operator.

Fisher Process Controllers

Fisher process controllers were incorporated into all these control loops. These controllers contain readouts for the controlled parameter, commanded setpoint and controller output signal, and adjustments for proportional loop gain, lag time constants and lead time constants. These controllers can be operated in either a manual mode or an automatic

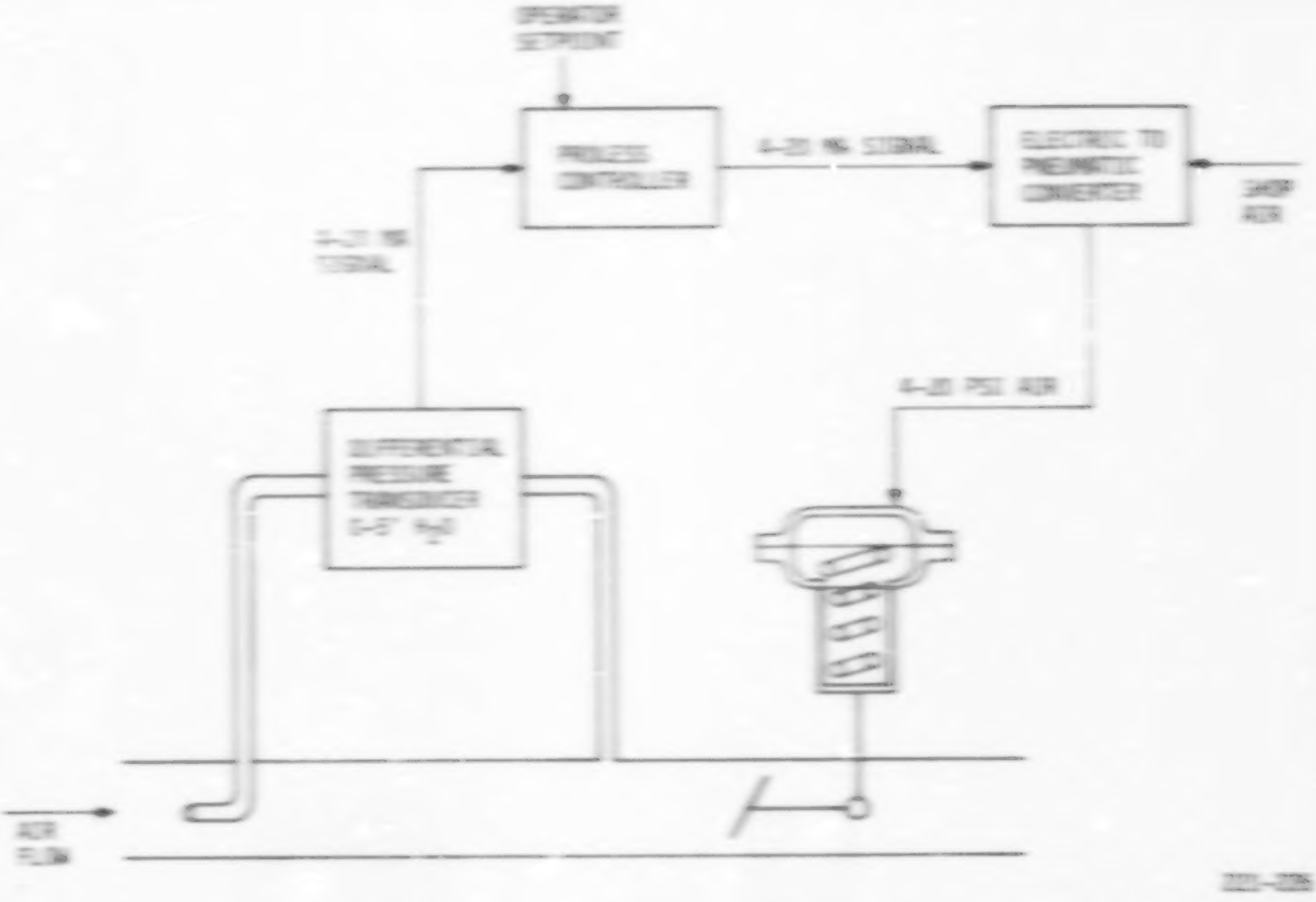

OPERATOR SETPOINT
PROCESS CONTROLLER
4-20 MA SIGNAL
ELECTRIC TO PNEUMATIC CONVERTER
SHOP AIR
4-20 MA SIGNAL
DIFFERENTIAL PRESSURE TRANSDUCER 0-5" H_2O
4-20 PSI AIR
AIR FLOW
221-226

Figure 4-7 Feedline Air Flow Control

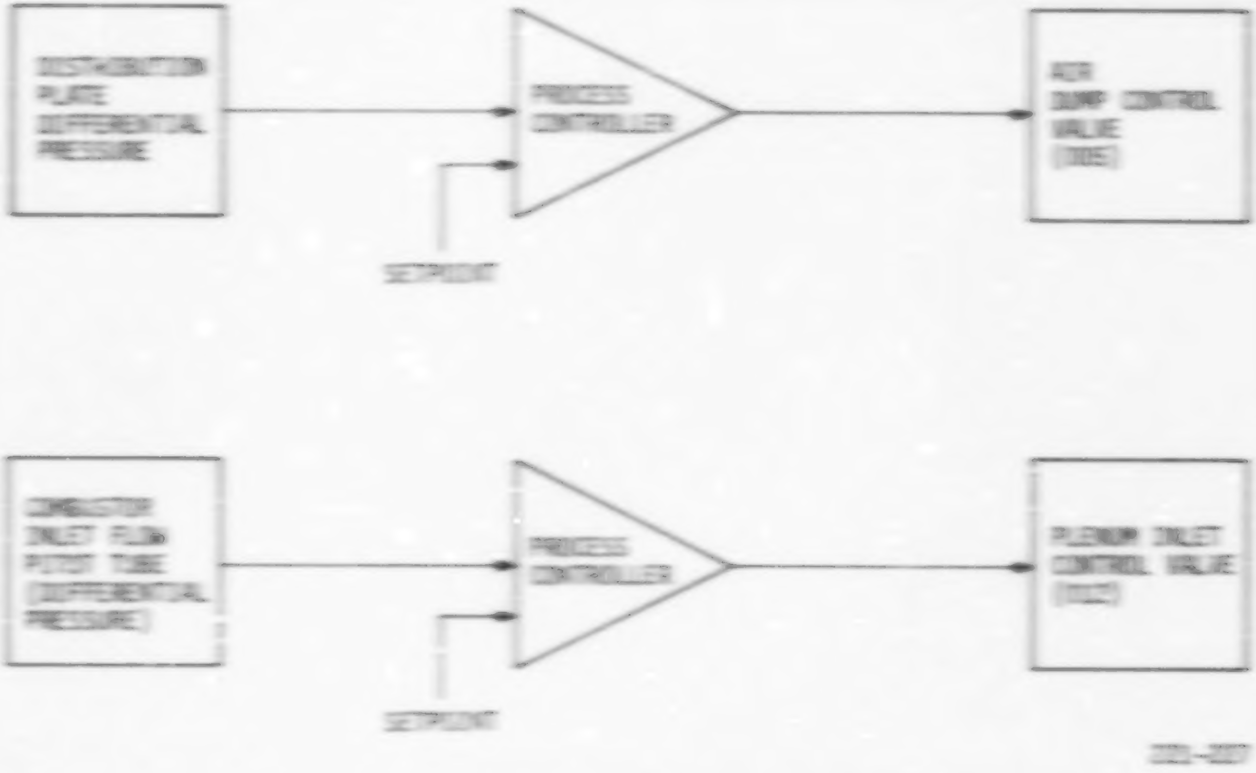

DISTRIBUTION
PLATE
DIFFERENTIAL
PRESSURE
PROCESS
CONTROLLER
SETPOINT
AIR
DUMP CONTROL
VALVE
(1005)
COMBUSTOR
INLET FLOW
PITOT TUBE
(DIFFERENTIAL
PRESSURE)
PROCESS
CONTROLLER
SETPOINT
PLENUM INLET
CONTROL VALVE
(1012)
221-207

Figure 4-8 Dump Air and Combustor Air Control Loops

mode. In the manual mode, the test conductor actuates a thumb wheel which causes an increase or decrease in the signal being sent to the associated unit controlled. A meter on the front of each controller provides an indication of the signal being sent to the controlled unit. In the automatic mode the process controller compares a signal from measurement of a preselected system parameter to a selected level or setpoint. A switch on each controller allows this setpoint to be set in locally by the operator or remotely by the computer. The controller then increases or decreases the signal to the controlled unit based upon the difference between the measurement and the setpoint.

Mode Switches

Starting and stopping the system and switching operating modes were accomplished through use of mode switches (Figure 4-9) designed to minimize the load on the operator. These switches were wired to preclude entrance or switching to any operating mode unless certain prerequisites were met. These prerequisites were established to insure that the system was ready for safe operation in the selected mode. When the prerequisites were met, the mode switch would turn on appropriate motors, valves, and sensors for the selected operating mode. If the prerequisites were not acceptable, the system operating state would remain unchanged. Also, if for some reason one of the prerequisites changed state during operation in a specified mode (indicating an unsafe condition), the system would automatically shut down.

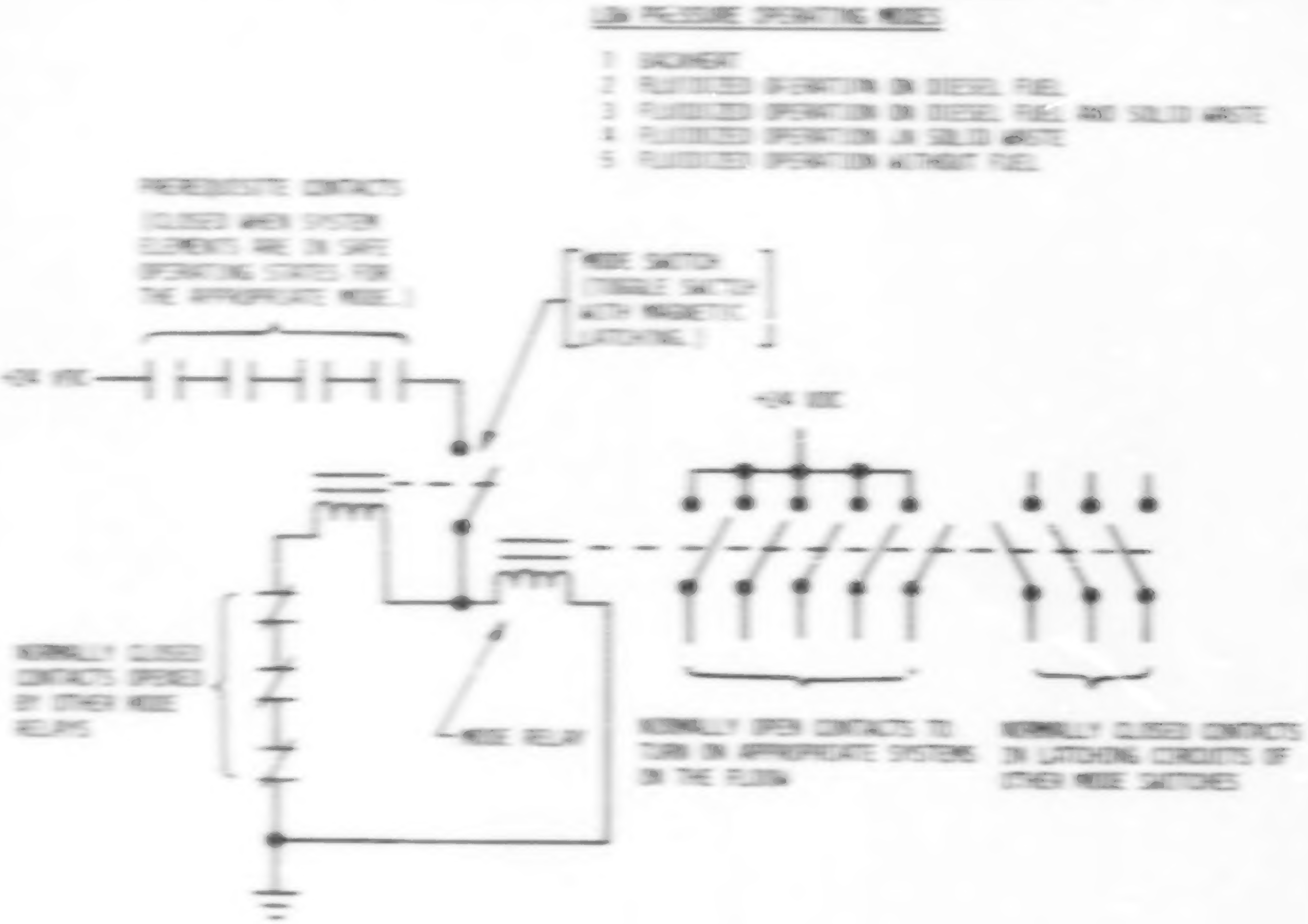

LOW PRESSURE OPERATING MODES
1 BACKVENT
2 FLUIDIZED OPERATION ON DIESEL FUEL
3 FLUIDIZED OPERATION ON DIESEL FUEL AND SOLID WASTE
4 FLUIDIZED OPERATION ON SOLID WASTE
5 FLUIDIZED OPERATION WITHOUT FUEL
PREREQUISITE CONTACTS
(CLOSED WHEN SYSTEM
ELEMENTS ARE IN SAFE
OPERATING STATES FOR
THE APPROPRIATE MODE.)
MODE SWITCH
(TOGGLE SWITCH
WITH MAGNETIC
LATCHING.)
+24 VDC
+24 VDC
NORMALLY CLOSED
CONTACTS OPENED
BY OTHER MODE
RELAYS
MODE RELAY
NORMALLY OPEN CONTACTS TO
TURN ON APPROPRIATE SYSTEMS
ON THE FLOOR
NORMALLY CLOSED CONTACTS
IN LATCHING CIRCUITS OF
OTHER MODE SWITCHES

Figure 4-9 Basic Mode Control Circuit Logic (Illustrated for Three Modes)

Temperature and Pressure Measurements

Instrumentation was primarily associated with temperature and pressure measurements. Thirty chomel-alumel thermocouples were distributed throughout the system. Two of these were used in the control system as previously noted; the remaining 28 were used for operational analysis. Six pressure (or pressure difference) measurements were required to define system operation and four pressure head (flow) measurements were used to monitor air flow. The location of the instrumentation is depicted in the test setup schematic applicable to each major test series discussed in Section V.

Data Acquisition System

Pressure and temperature measurements were recorded in a data acquisition system (Figure 4-10 and 4-11). A scanner, digital clock, data coupler, teletypewriter, digital temperature indicator, and a digital multimeter comprise this system.

The scanner transfers multiple analog input signals sequentially, under internal control, to a common set of output lines. Numbered front panel pushbutton switches permit skipping of unwanted channels. The pushbuttons are illuminated during the scan cycle to notify the operator of the scanner's position. A digital clock controls the scan process through 63 different selectable time intervals and provides a time heading for the data prior to each scan.

A data coupler resembles a small, hard-wired processor. It consists of a mainframe, data control buses, device input cards, device output cards,

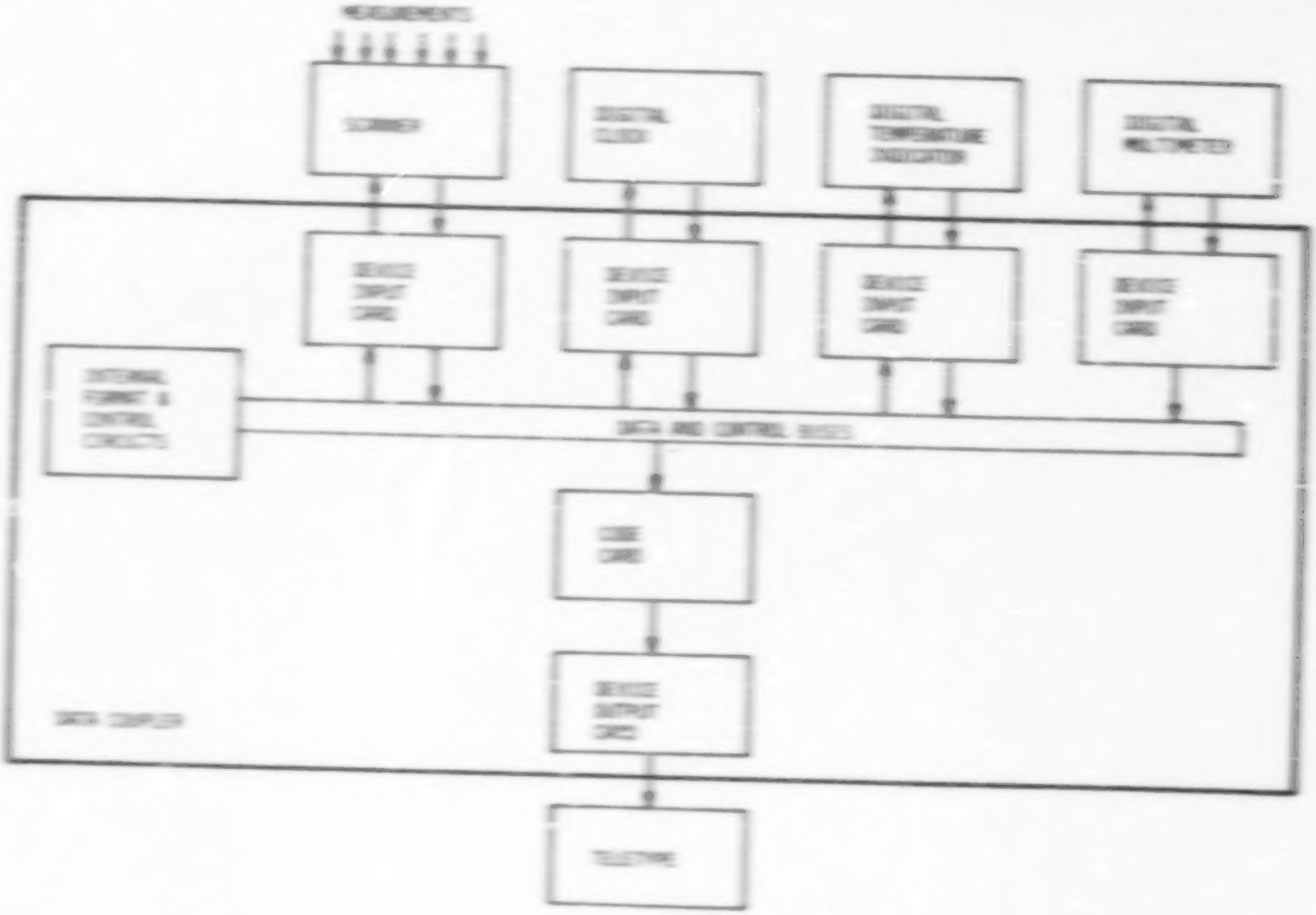

MEASUREMENTS
SCANNER
DIGITAL CLOCK
DIGITAL TEMPERATURE INDICATOR
DIGITAL MULTIMETER
DEVICE INPUT CARD
DEVICE INPUT CARD
DEVICE INPUT CARD
DEVICE INPUT CARD
INTERNAL FORMAT & CONTROL CIRCUITS
DATA AND CONTROL BUSES
CODE CARD
DEVICE OUTPUT CARD
DATA COUPLER
TELETYPE

Figure 4-10 Data Acquisition System Block Diagram

Figure 4-11 Data Acquisition System

code cards, and formatting matrices. This unit couples the digital output devices (multimeter, thermometer, or clock) to the teletypewriter; and it also allows for formatting the data (i.e., provides the capability to include engineering units in the record).

Thermocouple measurements are converted from millivolts to temperature via the digital temperature indicator. This unit provides linearization for the thermocouples (type K) along with a reference junction compensation. Voltage and resistance measurements are made via the digital multimeter. This unit is capable of autoranging and of having the mode externally selected.

DESIGN AND DEVELOPMENT OF AN AUTOMATIC CONTROL SYSTEM

The automatic control system was designed to provide full control of the pilot plant with a minimum of operator intervention. This includes automatic verification of system readiness, automatic verification of valve operability, automatic transition from one operating mode to another, and automatic monitoring of the system for alarm or out of tolerance conditions.

Location of Controls

Most of the automatic control system controls are located in a centrally situated overhead control room adjacent to the pilot plant. Some of the control operators, dedicated to specific elements of the system, are located in the proximity of the controlled unit in order to reduce cable run lengths and to reduce the number of signals being sent to the control room.

The control area is a two-story arrangement with signal conditioning, patch panels, transmitters and terminal strips located on the lower floor, while the control consoles and a process control computer are located above in the control room (Figure 4-12). Where practical, control and instrumentation (data gathering) functions are separated in order to minimize interference during system operation. Air conditioning and conditioning of the electrical power for the control system are provided in order to insure reliable operation of the electronics.

Process Control Computer

The primary function of the computer is to control the pilot plant process through an entire operating cycle. This includes monitoring of various operations within the process for out-of-tolerance or abnormal conditions. In this capacity, the system operates as a real time computer, the performance of each operation being based on a specific time for execution. A basic block diagram of the computer with the process is shown in Figure 4-13.

A background function of the computer during this process control function is data acquisition; reading various voltages, converting these voltages to engineering units, processing the information, storing the results and/or printing, punching, or recording the information on one of the digital system output devices.

The process control computer selected for this application is the Texas Instruments Model 960A Digital Computer. It is shown schematically in Figure 4-14. The following paragraphs provide a brief description of each major element in this system.

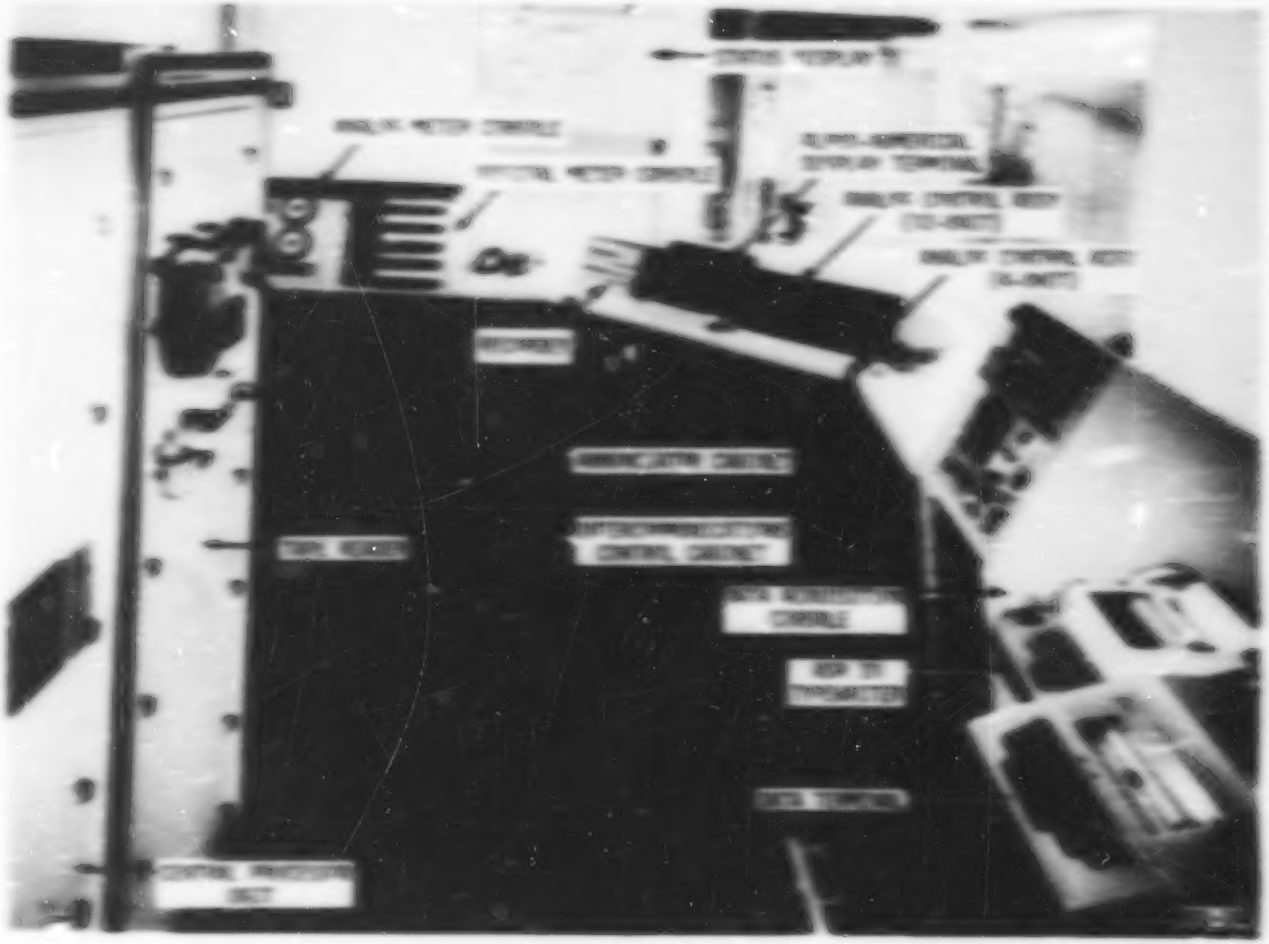

STATUS DISPLAY
ALPHA-NUMERICAL DISPLAY TERMINAL
TAPE READER
CENTRAL PROCESSING UNIT
DATA TERMINAL

Figure 4-12 Pilot Plant Control Room

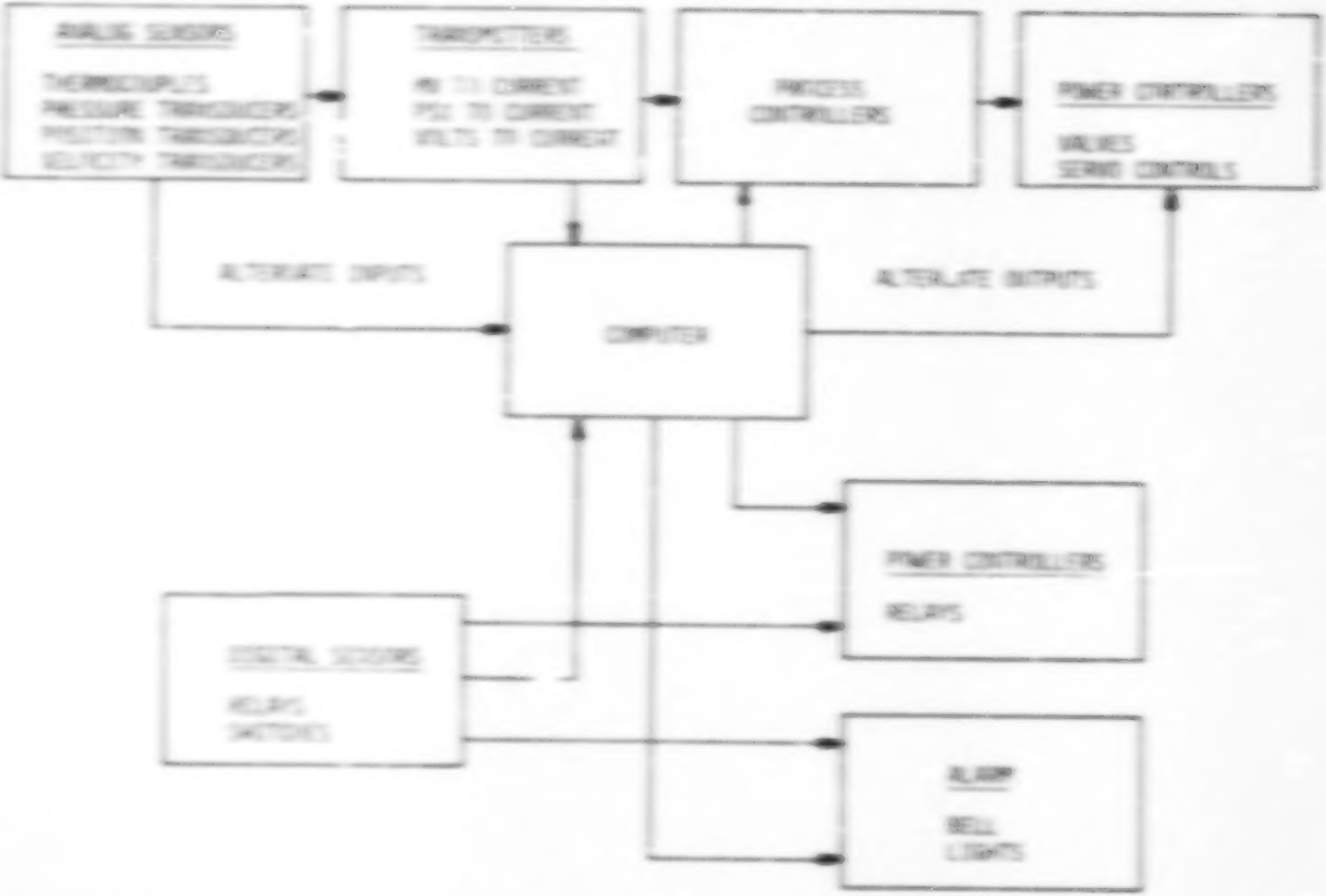

ANALOG SENSORS
THERMOCOUPLES
PRESSURE TRANSDUCERS
POSITION TRANSDUCERS
VELOCITY TRANSDUCERS
TRANSMITTERS
MV TO CURRENT
PSI TO CURRENT
VOLTS TO CURRENT
PROCESS CONTROLLERS
POWER CONTROLLERS
VALVES
SERVO CONTROLS
ALTERNATE INPUTS
COMPUTER
ALTERNATE OUTPUTS
POWER CONTROLLERS
RELAYS
DIGITAL SENSORS
RELAYS
SWITCHES
ALARM
BELL
LIGHTS

Figure 4-23 Generalized Control System Schematic

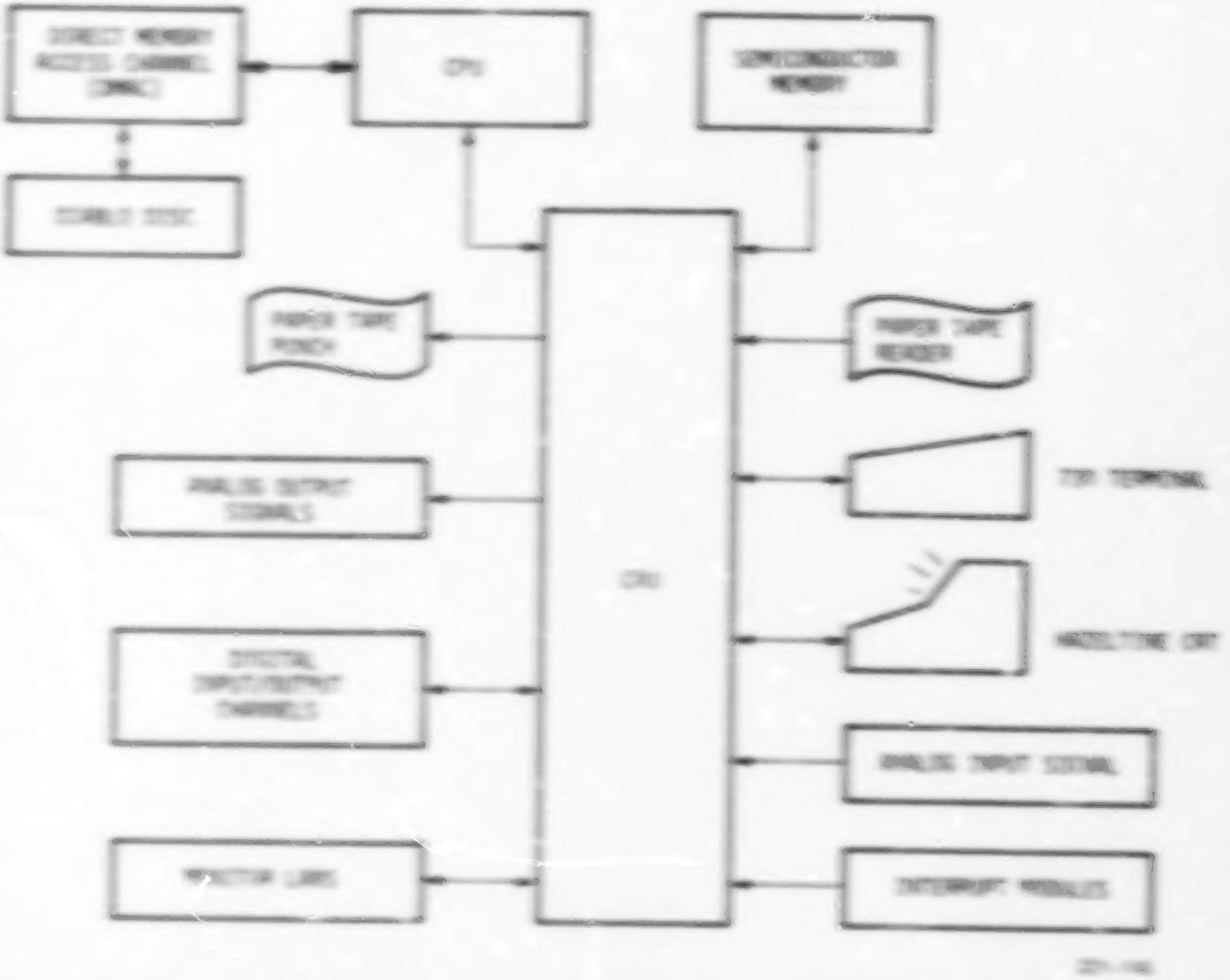

DIRECT MEMORY ACCESS CHANNEL (DMAC)
CPU
SEMICONDUCTOR MEMORY
PAPER TAPE PUNCH
PAPER TAPE READER
ANALOG OUTPUT SIGNALS
TTY TERMINAL
HAZELTINE CRT
DIGITAL INPUT/OUTPUT CHANNELS
ANALOG INPUT SIGNAL
INTERRUPT MODULES

Figure 4-24 Computer System Block Diagram

Central Process Unit:

The heart of the system is a 16-bit word length mini-computer (CPU) with 20,480 words of semiconductor main memory, a battery pack for continuous memory refreshing, memory parity, variable length memory protect, power failure interrupt, extended arithmetic option, expanded internal communications register unit (CRU) which provides for computer/process interfacing, and a control panel with a keylock.

Mass Data Storage Unit:

The mass storage unit is a 1.14 million, 16-bit word moving head Diablo disc pack and controller. It interfaces directly with the CPU through a direct memory access channel (DMAC). The disc pack has an average access time of 100 ms, and is used for process program compilation, process task storage, process data storage, task overlay operations, systems generation, and for storage of overall systems process control program configuration.

Telewriter:

The silent 700 teletypewriter is a 30-character per second teletype that is used as the system's main data logging device, and the primary programmer's interface peripheral.

Alpha-Number Display Terminal (CRT):

The CRT is an alpha-numeric display terminal with a maximum data transfer rate of 2400 baud. This device is used as the primary process operator's interface peripheral.

Paper Tape Punch Unit (PTP)-

The eight column paper tape punch unit is a 60-character per second device that is used for permanent storage of process source programs and process data.

Paper Tape Reader Unit (PTR)-

The paper tape reader unit (eight columns) is a 300 character per second device that is used to load memory from source tapes, and from stored process data tapes.

Interval Timer-

The interval timer is a 1 ms resolution device that provides controller/process synchronization, and a system's real time clock capability for time of day acquisition and recording.

Low Level, Differential, Analog Input Subsystem-

The low level A/D subsystem provides 30 channels of 0.05 percent accurate, low level analog inputs for measurement of process temperatures utilizing the thermocouple method.

High Level, Single-Ended, Analog Input Subsystem-

The high level A/D subsystem provides 80 channels of 0.05 percent accurate, high level analog inputs for measurement of process transducer outputs. Some examples of process outputs are pressure, level, speed, position, setpoints, voltage, current, power, flow rate, and weight.

High Level, Single-Ended, Analog Output Subsystem-

The high level analog output subsystem provides 18 channels of 0.05 percent accurate, high level analog outputs for process setpoint generation.

Discrete Contact Closures (11)-

The 160 sets of isolated, buffered, contact closures are used to control the energizing and de-energizing of numerous process control relays and contactors for programmed sequential plant operation.

Discrete Contact Sense (12)-

The 160 channels of the discrete contact sense subsystem are used to monitor numerous process contact closures, to ensure correct sequential plant operation, and to indicate urgent and semi-urgent process alarm conditions.

Digital Input Subsystem (13)-

Thirty-two bits of the 96-bit digital input subsystem are used to monitor the modes of operation of the various process controllers. The remaining 64 bits are used in conjunction with the 64-bit digital output subsystem to interface the computer system with the process data acquisition system.

External Interrupt Subsystem-

The 16-channel external interrupt subsystem is used to generate immediate mode process alarm conditions, to get supervisor control for certain peripheral devices, and to get immediate operator control of the process under predefined conditions. Each external interrupt will cause the computer to trap the predefined memory locations for programmed servicing of that particular interrupt.

Software

The remainder of this section describes the software approach to the process control, monitoring, and data acquisition functions.

Vendor Supplied Software-

To accomplish the required operations in a real time environment, a multi-programming operating system denoted PAM/D[*] was utilized on the Texas Instruments (TI) model 960A computer. The PAM/D monitor system uses an executive worker method of program control and incorporates a multi-level priority scheme for program execution.

Several high priority software elements ("tasks") are supplied by TI as part of the PAM/D system and are available throughout all process operations. Two of these, denoted DEBUG and JOB CONTROL, provide a basic means of directing and controlling the execution of application-oriented tasks. These software packages comprise the principal interface between the programmer and the computer during program development phases. Following initial development, however, many of the important functions performed by these packages can more efficiently be handled by a high priority, pilot plant process oriented task. In this approach test conductor personnel can communicate with the process and the computer in familiar terms, thus avoiding the need to become proficient in DEBUG and JOB CONTROL coding. Accordingly, little additional attention is addressed to these software elements in the remainder of this discussion.

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[*] An acronym for Process Automation Monitor/Disc

A basic decision was made to employ the PCL[†] language wherever possible in implementing pilot plant software. The relatively high level PCL language offers numerous programming advantages such as ease of expressing arithmetic operations on real numbers, convenience in certain types of control and input/output (I/O) operations, and reduced actual programming labor costs. Nevertheless, there is a significant list of limitations and constraints in the present version of PCL; this list clearly indicates that PCL should not be expected to compete with contemporary large-machine FORTRAN compilers.

The next highest level language supplied with the 960A is the Symbolic Assembly Language (SAL)[‡]. This language, which produces machine language code in a two-pass assembly, includes a relatively powerful set of 78 basic instructions. Since PCL uses a one pass compiler to produce a corresponding re-entrant SAL program, it is possible to include in-line SAL coding commands in the original PCL program. This technique, to be avoided wherever possible, unless particularly advantageous, can be used to remove some of the PCL limitations.

[†] An acronym for Process Control Language, an extension of ANSI basic FORTRAN II.

[‡] A SAL command in a PCL program, distinguished by a period in the first column, is passed through compilation intact to join compilation generated commands. One example of necessary SAL coding is to interrogate the real time clock in order to generate the time of day.

Another important element of vendor-supplied software, known as LIB/LNK960**, is utilized to link the object modules produced by the assembler for main programs and the required subroutines. Output from this program constitutes the overall object tape which can be loaded for execution by the computer.

Pilot Plant Software Structure-

The multiple task capability of the TI960A was fully utilized in the applications software written for the pilot plant. A set of 23 tasks comprise the process control software configuration used for low pressure pilot plant testing operations.

In the PAM/D operating system it is possible to have one task bid another. It is also possible for a task to "suspend" itself. In the suspended state, a task remains in memory with its instruction counter fixed at a known statement in the program. This state can be terminated by one of two methods. First, another executing task can "unsuspend" the task whenever specific conditions are satisfied. Secondly, a specific programmed external discrete signal from outside the computer can be used. This external signal can be either a process oriented contact sense line or an operation oriented switch line.

The foregoing capabilities have been developed into concepts of "executive" and "worker" tasks. In the pilot plant software, for example,

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** An acronym for Library Link

The overall executive task 10 is first bid by the operator using a DEBUG command. Most of the subsequent task bidding is then performed automatically by the tasks themselves. Typically, for the greater percentage of the time, executive tasks are in the suspended state, waiting to be unsuspended by either an interrupt or a worker task that has completed some prerequisite activity.

A basic feature of the PAM/D system is that many tasks may be in the "bid" state simultaneously. These tasks are loaded into various separate portions of the computer memory (management of this function being a prime attribute of PAM/D) and receive attention according to their various assigned priority integers. Each 0.1 second a new scan of bid tasks is begun by the monitor and those tasks that are not suspended are serviced.

Common data base - The principal means of inter-task communication is a system-wide common data base (CDB) that is accessible to all tasks. The CDB itself occupies a special portion of computer memory beginning with hexadecimal location B0 and extending for 426 words.

A discussion of the CDB reveals many of the software structural design concepts. The structure is precisely defined by the group of PCL COMMON and DIMENSION declarations shown in Table 4-1. The meaning and use of the various variables cited in the table are summarized below:

INDXI A 72 row by 2 column array of integers that form an index and scan control scheme for the analog input channels sampled by the computer. Information pertaining to the 3-digit CPC mea-

Table 4-1. COMMON DATA BASE DEFINITION FOR LP-11

Declaration	Variable
COMMON	(OBO) INDXI, MDATA, NMEAS, IMEAS
COMMON	INDXO, MOUTP, NOUTP, IOUTP
COMMON	PARAM
COMMON	MODE, IQUIT, IREAD, ILI
COMMON	IDLES, LTIME
COMMON	LOG, MSTAT, STAT
DIMENSION	INDXI (72,2), MDATA (72)
DIMENSION	INDXO (18), MOUTP (18)
DIMENSION	PARAM (60)
DIMENSION	LTIME (4)
DIMENSION	MSTAT (20), STAT (10)

	surement number, the high (or low) level of the signal, and the sampling frequency is packed into the first column for each channel. The analog converter channel number is stored in the second column.
MDATA	A 72 member array of integers that contain the most recent results of sampled, digitized conversions on each of the analog input channels. The measurement associated with the ith row of INDXI appears in the ith element of MDATA.
NMEAS, IMEAS	A pair of integers that implement an asynchronous operator or programmatic command for a read of a specific measurement. Together with the automatic periodic sampling, this mechanism is presumed to maintain sufficiently current information in the MDATA array about the process state.
INDXO	This integer array associates a 3-digit CPC number with each of the 18 available analog input channels. It thus provides an index function that enables program reference to the CPC numbers.
MOUTP	This 10 member integer array is a register for the last output values sent from the computer to each of the analog output channels.
NOUTP, IOUTP	Two integers used in a way similar to NMEAS and IMEAS for operator introduced changes to analog output channels.
PARAM	A 60 element real number array containing adjustable parameters for process control and monitoring. Certain key measurements in engineering units are also stored here. A computer readout

	of this array is presented in Figure 4-15.
MODE	An integer that reflects the commanded mode of pilot plant operation. For example, MODE=1 pertains to bed preheat operations.
IQUIT	Task termination integer. Most looping tasks look to this number; if their ID number occurs, they branch to terminate.
IREAD	An integer argument of a WAIT statement that determines the basic analog input sampling frequency. Frequency ≅ 0.1/(IREAD+1) reads/second.
ILI	An integer for general task control communication purposes.
IDLES	An integer argument of a WAIT statement for timing control between the executive logging tasks and their worker tasks.
LTIME	An integer array where the start time (year, day of year, hour minute, and second) associated with the task 50 (i.e., fluidized operations) start point is stored.
LOG	An integer argument of a WAIT statement that determines the basic logging frequency. Same relationship as for IREAD.
MSTAT	An array of integer state variables involved in digital filtering of analog input measurements.
STAT	An array of real state variables involved in digital filtering of computed performance parameters (e.g., flow rates).

Many of the common data base elements are filled with initial values by reading from a disc data file at the beginning of software operations. Those initialized in this fashion include INDXI, INDXO, PARAM, and IREAD. The display in Figure 4-15 is a listing of that portion of the

```
[illegible]  [illegible]  [illegible]  PREHEAT AIR FLOW SET POINT, LB/MIN
[illegible]  [illegible]  [illegible]  PREHEAT AIR FLOW CONTROL P GAIN, GAIN
[illegible]  [illegible]  [illegible]  PREHEAT AIR FLOW INT. GAIN
[illegible]
```

Figure 4-15 Parameter Section of Common Data Base

disc file that is used as a source for the initial PARAM array.

A summary identification of the 23 tasks used is contained in Table 4-2. In Table 4-3, a normal chronological sequence of events is outlined to provide additional insight. For reference, a PCL listing for the principal task, task 50, is included as Figure 4-16.

Executive task 10 commands - A major function of executive task 10 is to provide an operator/computer/process interface at the CRT console. As previously noted, task 10 is normally suspended and waiting for an interrupt. The external devide providing the interrupt is the ACCEPT button near the CRT: depression by the operator constitutes the interrupt that unsuspends the task.

After interruption, task 10 normally calls a communication subroutine that receives one of several commands from the CRT keyboard. These commands begin with a two-character code that is normally followed by a three-digit integer, and may be followed by an additional value. The definition of the commands used in LP-11 testing are described in Table 4-4.

It should be noted that all DEBUG and JOB CONTROL commands are available during process control operations. This provides a straightforward method for real-time display and modification of all integers in the CDB, including the index array elements.

Table 4-2. TASK IDENTIFICATION SUMMARY

I.D.	Description
10	Overall execution
A2	Reads initial CDB data, zeroes all outputs
20	Analog input scan
30	Controller readiness checks, transducer zeroes
31	Valve exercise
32	Preheat mode initialization
33	Preheat mode ignition, control, and monitoring
50	Fluidized operation control and monitoring
15	Preheat logging executive
80	Preheat control parameter logging
81	Preheat pressure and temperature logging
17	Fluidized logging executive
83	Data filtering - high speed
84	Data filtering - low speed
85	Solid waste flow logging
86	Bed temperature logging
87	System pressure logging
88	System pressure drop logging
89	Miscellaneous temperature logging
8B	Proportional valve position logging
8C	Control system parameter logging
8D	Air flow calculation and logging
8F	Time origin logging

Table 4-3. COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event

1. The DEBUG command actuated by the operator bids task 10, the primary executive task.
   a. Task 10 bids task A2 to initialize the common data base (CDB) with values read from disc file D4.
      (1) IREAD, an integer that (roughly) says how many seconds between each basic analog input scan cycle.
      (2) 72 sets of MEAS, LEVEL, IFREQ, NCHAN integers to form the INDXI array for analog input channel scanning.
      (3) 16 integers of the INDX0 array for analog output.
      (4) 60 real values to initialize the parameter array.
   b. Task 10 bids task 20, the analog input scan task.
   c. Task 10 bids task 30, the pre-test health check task (see step 3).
   d. Task 10 then suspends itself to wait for the ACCEPT button interrupt. If interrupted, it writes a message ("waiting for task 30 to terminate") and checks to see if task 30 is done. If not, it loops back to wait for another ACCEPT interrupt. If done, see step 4.

2. Task 20 immediately starts scanning 72 analog input channels, storing the resultant digitized conversions in appropriate elements of the MDATA array. The MDATA array is also part of the CDB so its contents are available to all other tasks.

   The periodic scan algorithm features 6 different input scan frequencies (unless a shared transducer is used) in addition to a "never read" choice if IFREQ=0 for the channel. An index, J, is cycled from 1 to 8, making a step every IREAD seconds.

   a. J index 1 -
      (1) C0730 and C0737 are closed so that pressures 101 and 123 are switched to transducers 101 and 123 for later reading when J = 2.

Table 6-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event

   (2) All channels with IFREQ=1 are read and stored in proper MDATA elements.

b. J Index 2 -

   (1) All channels with IFREQ=1 or 2 are read and stored.

   (2) Pressures 101 and 123 are read and stored in MDATA(30) and MDATA(37). C0730 and C0737 are opened.

c. J Index 3 -

   (1) C0731 and C0738 are closed so that pressures 102 and 124 are switched to transducers 101 and 123 for later reading when J = 4.

   (2) All channels with IFREQ=1 are read and stored.

d. J Index 4 -

   (1) All channels with IFREQ=1,2,4 are read and stored.

   (2) Pressures 102 and 124 are read and stored in MDATA(31) and MDATA(38). C0731 and C0738 are opened.

e. J Index 5 -

   (1) C0734 and C0739 are closed so that pressures 107 and 125 are switched to transducers 101 and 123 for later reading when J = 6.

   (2) All channels with IFREQ=1 are read and stored.

f. J Index 6 -

   (1) All channels with IFREQ=1 or 2 are read and stored.

   (2) Pressures 107 and 125 are read and stored in MDATA(3[illegible]) and MDATA(39). C0734 and C0739 are opened.

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event

g. J Index 7 -

    (1) All channels with IFREQ=1 are read and stored.

h. J Index 8 -

    (1) All channels with IFREQ=1,2,4 or 8 are read and stored.

3.[a] Task 20 returns to reset J=1 repeatedly until it sees IQUIT=20, the latter having been set by the executive task 10 when it decides to stop 20. In that case, task 20 opens all contact closures, sets IQUIT to 0, and terminates.

4. Task 30 is a pre-test health check task that accomplishes the following in a one-pass sequence:

    a. Writes an initial message (CRT and 700).

    b. Verifies that protectal system contact CI733 is closed. If not, it writes a message, and continues checking every second. When corrected, the task writes an OK message before continuing. On the other hand, if there *never was* a fault, no message is written at all; the task simply moves to the next check at once. This same pattern is followed in succeeding checks.

    c. Verifies that CI615 is closed indicating sufficient facility air pressure.

    d. Checks each of eight pressure transducers to see whether they are putting out 1 vdc ± 0.1 (i.e., 0 psig). The sequence is: 121, 120, 146, 140, 141, 101, 123, and 142.

    e. Verifies that CI706 is closed indicating a satisfactory diesel oil level.

---

[a] Two other contact closures are controlled by task 20. At every step in J, the task looks at MODE (also in COB). If MODE = 1 (as in the present case), C0735 and C0744 are closed to switch polarity of pressure transducers 120 and 121 for the preheat mode. Otherwise, they are opened.

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step Event

f. Verifies that C1730 is closed indicating that the transfer conveyor belt has not drifted.

g. Verifies that C1731 is closed indicating that the weighing conveyor belt has not drifted.

h. Verifies that five temperature transducers are operable by checking for an open condition on the following:

C1506	(Bed)
C1507	(Freeboard)
C1504	(1/S2 outlet)
C1503	(A/S top)
C1505	(1/S1 outlet)

i. Displays recommended settings for controllers 1 through 8, in turn, pausing after each message with an ATTENTION note. Pressing CONTINUE causes the task to move on.

j. Verifies that each of 7 "remote setpoint" switch controls are closed.

Contact	Controller
C1905	1
C1986	3
C1980	4
C1982	5
C1983	6
C1984	7
C1971	8

k. Writes some termination messages, sets IQUIT=30 (for executive task 10 in step 4), and terminates.

5. Now that task 30 has concluded, task 10 bids the valve exercise task 31 and again suspends itself waiting for an interrupt at the ACCEPT button. If interrupted in this loop it writes a different message and checks to see if task 31 is done (i.e., IQUIT=31). If not, it loops back for another ACCEPT interrupt. If 31 is done, see step 7.

6. Task 31 moves various system valves and verifies appropriate response from associated position transducers and/or switches. It also is a one-pass task.

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event
a.	Task 51 first writes two opening messages, one of which is a suggestion to advise personnel to stand clear of the valves. Then it pauses; press C0NTINUE to move on.
b.	Dump valve 005 should initially be closed because of the shorting contact (C0020=0). This is verified (CI736=1 and CI223<0.1 vdc). Then C0020 and C0014 are closed so that controller 1 can receive a setpoint of -3.0 volts from C0005. Within 8.0 seconds the computer looks to see if CI736=0 and CI223>9.5 vdc as should happen if the valve goes full open. In each case above, failure produces a message and a pause. Then pressing C0NTINUE starts a new try. When successful an OK message occurs and the task moves on. Valve 005 is left open for preheat. This same general pattern is repeated in the following steps:
c.	Air plenum inlet valve 007 is commanded closed (it may already be closed) by 1.0 volts on C0007 through controller 2. Contact C0013 is first closed to permit this. The verifications are CI724=open, CI725=closed, and CI222<0.1 volts. Then 5.0 volts is put on C0007 and the task later looks to see if CI724=closed, CI725=open, and CI222>9.5 volts. Valve 007 is left open for preheat.
d.	Five valves are then cycled open and closed in turn. In each case, first 5.0 volts and then -3.0 volts are applied to a specific analog output channel and a potentiometer signal is monitored.

Valve	Prior digital outputs	Analog output channel	Analog Xducer
Diesel oil 002	C0022 = 1 C0008 = 1 C0009 = 0 C0010 = 0	050	236
Feed line 000	C0011 = 1	000	220
Feed line 001	C0012 = 1	001	221
I/S1 Residue 009	C0025 = 1	009	225
A/S Residue 010	C0016 = 1	010	226

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event
	e. Feed line air shutoff valve 729 is opened. The valve is left open for preheat.
	f. Preheat air shutoff valve 704 in opened using C0704=1. It is left open for preheat.
	g. The task writes some termination messages, sets IQUIT=31 (for executive task 10 in step 5), and terminates.
7.	After task 31 concludes, task 10 bids the preheat initialization task 32 and again suspends itself waiting for an interrupt at the ACCEPT button. It remains in this loop, able to service operator CRT commands, until IQUIT=32 is observed.
8.	Task 32 conducts the following operations preceding ignition of the preheat burner:
	a. Positions system valves for the preheat operating mode,
	b. Turns on appropriate residue removal system components to implement a purge exercise,
	c. Turns the main blower on,
	d. Steps valve 007 partially closed to set up an initial air flow condition through the preheat burner,
	e. Implements a 30 second preheat air flow control loop so that measured flow approaches the value stored in parameter 01,
	f. Turns off the residue removal system components,
	g. Sets IQUIT=32 to inform task 10 of completion.
9.	After task 32 concludes and ACCEPT is depressed, task 10 bids preheat ignition and control task 33. It then enters a loop containing the usual suspend-on-ACCEPT interrupt feature.
10.	Task 33 takes over the preheat sequence, performing the following operations:
	a. Initiates preheat logging executive task 15 (see item 10).

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

Step	Event
	b. Generates the ignition spark pulse, opening the propane valve and oil valves, checking for established flame,
	c. Continues the burner air flow control begun in step 8e,
	d. Refreshes a setpoint output to controller 3 for analog comparison with measured freeboard temperature (and subsequent oil flow control),
	e. Monitors bed, freeboard, and inertial separator stage 2 outlet gas temperature,
	f. Initiates a termination shutdown sequence when bed temperature exceeds the readiness value stored in parameter 24. Included is setting IQUIT=33 to communicate with task 10 in the normal way. Also included is termination of preheat logging executive task 15.
11.	Preheat logging executive task 15 is active in parallel with task 33. It first bids task BF which stores a time origin on disc file B4, and then periodically bids two worker tasks during preheat operations:
	a. Task B0 logs 11 control parameters of interest,
	b. Task B1 logs 11 selected pressures and temperatures.Logging frequencies for the two tasks are individually adjustable.
12.	After task 33 concludes and ACCEPT is depressed, task 10 bids fluidized control and monitoring task 50. It then enters a loop containing the usual suspend-on-ACCEPT interrupt feature (see step 15).
13.	Task 50 supervises and monitors operations in the fluidized mode. Actions include the following:
	a. Appropriate pre-positions system valves,
	b. Activates residue removal system components (transport blower, baghouse motors, valves, hopper vibrators),
	c. Activates main blower,
	d. Bids fluidized logging executive task 17,
	e. Refreshes valve 007 position command based on parameters 36 and 37,

Table 4-3 (Continued). COMPUTER SOFTWARE TIME SEQUENCE OF EVENTS

f. Supervises control of the setpoint to controller 4 such that T031 approaches the value stored in parameter 48,

g. Refreshes the setpoints for feedline air flow controllers,

h. Monitors bed, freeboard, and first stage separator top temperatures,

i. Performs bang-bang control of bed temperature by opening/closing bypass valve 704,

j. Generates a periodic CRT and 700 log display,

k. Conducts an orderly shutdown sequence including terminating executive logging task 17.

14. Fluidized logging executive task 17 is active in parallel with task 50. It first bids task BF to store a time origin on disc file 84. Then it periodically bids a string of worker tasks, most of which also generate disc file records.

a. Task B3 digitally filters data to be logged by tasks B5 and B7.

b. Task B4 digitally filters data to be logged by task BA.

c. Task B5 logs solid waste flow rate and cumulative values.

d. Task B6 logs bed temperatures.

e. Task B7 logs system pressures

f. Task B8 logs system pressure drops.

g. Task B9 logs miscellaneous system temperatures

h. Task BB logs proportional valve positions.

i. Task BC logs control system performance parameters.

j. Task BD computes and logs system air flow rates.

15. After bidding task 50, executive task 10 is normally suspended in an operator service loop. The only exit from this loop is through setting IQUIT=10. When task 50 and other tasks have terminated, this is the normal final step in clearing the memory of all tasks.

```
C
C  FLUIDIZED CONTROL TASK 050
C
      COMMON /ZBO/ INPUT, MDATA, IREAL, IREAL
      COMMON INPO, MOUTP, AOUTP, IOUTP
      COMMON PARAM, CD05U,T00D,T0[illegible],T014,T031,T037
     $       ,T072,P101,P107,P120,P121
      COMMON MODE,IOUT,IREAD,IL
      DIMENSION INPUT(72,2), MDATA(72)
      DIMENSION INPO(10), MOUTP(10)
      DIMENSION PARAM(49)
      FLAG EPA, WAITB
C
C  CRU SPECIFICATIONS
C
      CRU OUTPUT CD505(5), CD506(6), CD507(7)
      CRU OUTPUT CD511(211), CD513(212), CD515(214)
      CRU OUTPUT CD516(215), CD518(216), CD519(217)
      CRU OUTPUT CD520(2208), CD701(2213), CD704(262)
      CRU OUTPUT CD706(2C2), CD708(203), CD709(2C4)
      CRU OUTPUT CD705(263), CD712(267), CD714(2219)
      CRU OUTPUT CD726(276), CD727(277), CD728(2216)
      CRU OUTPUT CD922(281),CD323(280)
      CRU INPUT PANIC(2F0),IS22W(2F1)
C
   LA 7,E          CRU BASE FOR DIGITAL I/O
C
C  BRANCH TO BOTTOM TO SOLVE THE OFF PROBLEM
C
      GOTO 5000
C
C  TURN MAIN BLOWER ON; UNIT IS SEC; CHECK FOR RESTART
C
  100 CALL ICMODE(6,4)
      CALL FFUIB
      CD520=1
      CALL FAOUT(0,1,56)
      CALL AAOUT(1,1,56)
   LA 3,=C'0017'         PID EXECUTIVE LOADING TASK 17
   CRBT #127             BRANCH TO [illegible]
C
C  TURN OIL GUN AIR AND COOLING WATER ON
C
      CALL [illegible](4)
      CD706=1
      CD712=1
C
C  IGNITION AND CONTROL LOOP
C
      [illegible]
      [illegible]
      [illegible]
      [illegible]
  100 CONTINUE
      [illegible]
      [illegible]
      [illegible]
  [illegible]
```

Figure 4-16 Task 50 Listing

```
C
C  VALVE 007 COMMANDS
C
      V7=PARAM(37)
      IF(V7-PARAM(36))370,380,380
  370 V7=PARAM(36)
  380 CALL ANOUT(7,V7)
C
C  BSC OF 1-52 OUTLET TEMPERATURE T031
C
      T031=TEMP(31)
      PARAM(47)=PARAM(48)-T031
      E=PARAM(47)
      VL= 1.0 + 0.002*PARAM(48)
      VU = VL + 0.3
      CD050=AMAX(VL,AMIN(VU,PARAM(44)+PARAM(45)*E))
      PARAM(44)=AMAX(VL,AMIN(VU,PARAM(44)+PARAM(46)*E))
  425 PARAM(42)=PARAM(48) + PARAM(49)
  430 CALL ANOUT(50,CD050)
      IF(EPA) GO TO 434
      IF(ABS(PARAM(47))-PARAM(42)) 432,434,434
  432 EPA=1
      CALL MSSGE(17,4)
  434 CONTINUE
C
C  OIL SYSTEM ON-OFF LOGIC
C
      GOTO(500,500,500,501,501),MODE
  500 CD022=1
      CD701=1
      CD515=1
      GOTO 502
  501 CD022=0
      CD701=0
      CD515=0
  502 CONTINUE
C
C  SOLID WASTE SYSTEM ON-OFF LOGIC
C
      GOTO(601,601,600,600,601),MODE
  600 CD505=1
      CD506=1
      CD507=1
      CD511=1
      CD513=1
      WASTE=1
      GOTO 602
  601 CD505=0
      CD506=0
      CD507=0
      IF(WASTE) WAIT(45)
      WASTE=0
      CD511=0
      CD513=0
  602 CONTINUE
```

Figure 4-16 Task 50 Listing (Continued)

```
C
C  UPDATE FEEDLINE AIR VALVE SET POINT
C
      CALL ANOUT(0,1,+0.0*PARAM(27))
      CALL ANOUT(1,1,+0.0*PARAM(28))
C
C  TEMPERATURE MONITORING
C
      T000=TEMP(0)
      T014=TEMP(14)
      T072=TEMP(72)
      IF(T014-PARAM(40))702,702,701
  701 CALL MSAGE(11,4)
  702 IF(T072-PARAM(41))704,704,703
  703 CALL MSAGE(12,4)
  704 IF(.NOT.EFA) GOTO 708
      IF(-PARAM(47)-PARAM(42))706,706,705
  705 CALL MSAGE(13,4)
      GOTO 708
  706 IF(-PARAM(47)+PARAM(42))707,708,708
  707 CALL MSAGE(14,4)
  708 CONTINUE
C
C  CHECK FOR TERMINAL OUTPUT LOG EACH MINUTE
C
      [illegible]
 .  L 0,L          LOAD L HDW 6
 .  BC 11,2000D          BRANCH IF TIME FOR DISPLAY
 2001 CONTINUE
C
C  BANG-BANG CONTROL OF BED TEMPERATURE WITH CD704
C
      IF(T000-PARAM(31))720,720,721
  720 CD704=1
      GOTO 723
  721 IF(T000-PARAM(32))723,722,722
  722 CD704=0
  723 CONTINUE
C
      K=K+1
      GOTO 300
C
C  SHUTDOWN SEQUENCES
C
  800 CD515=0
      CD701=0
      CD522=0
      CD505=0
      CD506=0
      CD507=0
      CD511=0
      CD513=0
      CALL ANOUT(7,0,0)
      CD712=0
      CD705=0
      CD520=0
```

Figure 4-16 Task 50 Listing (Continued)

```
      CO728=0
      CO727=0
      CO726=0
      CO709=0
      CO708=0
      CALL ANOUT(10;1,0)
      CO704=0
      GOTO 102
  900 CALL MSAGE(15;4)
      WAIT(300)
      IF(ILI)102;950;102
  950 CALL MSAGE(16;4)
      IQUIT=50
      ILI=0
      GOTO 999
C
C  TERMINAL OUTPUT LOG SECTION
C
 2000 WRITE(2;4) E/6; T000;T014;T072;T031
      WRITE(1;4) E/6; T000;T014;T072;T031
    4 FORMAT(I5,'   BED =';F7.1;'   FBD =';F7.1;'   A/S =';F7.1;
     1 '   T/S2 =';F7.1)
      GOTO 2001
C
C  TASK INITIALIZATION
C
 3000 CONTINUE
      CALL MSAGE(1;4)
      CALL MSAGE(2;4)
      CALL PAUSE
C
C  RESTART POINT AND CHECK FOR TASK TERMINATION
C
  100 IF(ILI) 102;104;102
  102 CALL MSAGE(3;4)
      ILI=0
      CALL PAUSE
  104 IF(IQUIT-50) 106;900;106
C
C  CONTROL FP 3 TAKES INPUT FROM A/S TOP TEMP 072
C
  106 CO823=0
C
C  OPEN VALVES 714; 008; 0101  CLOSE 002; 005; 704
C
      CALL MSAGE(4;4)
      CO704=0
      CALL ANOUT(9,5,0)
      CALL ANOUT(10;5,0)
      CO822=0
```

Figure 4-16 Task 50 Listing (Continued)

```
C
C   TURN HOPPER VIBRATORS; TRANSPORT AIR ON.
C
      CD708=1
      CD709=1
      CD726=1
      CD727=1
      CD728=1
      GO TO 130
C
C   END LABEL
C
  999 CONTINUE
      END

 USER SUBPROGRAMS REQUIRED:

    **  MERGE   **
    **  PAUSE   **
    **  ANOUT   **
    **  TEMP    **
    **  AMIN    **
    **  AMAX    **
```

Figure 4-16 Task 50 Listing (Continued)

Table 4-4. TASK 10 EXECUTIVE COMMANDS

Command	Definition
DINNN	Display analog input having measurement number NNN (uses INDXI array for index)
DONNN	Display analog output having CPC number NNN (uses INDXO array for index, MOUTP array for value)
DPNNN	Display parameter (PARAM array) with subscript NNN
SPNNN XX.XX	Set parameter with subscript NNN to value given by XX.XX
SONNN XX.XX	Set output having CPC number NNN to voltage given by XX.XX
SL	Go back to sleep (i.e., resuspend the task)
IQNNN	Set CDB integer IQUIT to value given by NNN
MONNN	Set CDB integer MOUT to value given by NNN

SECTION V

INTEGRATED SYSTEM TESTS

As defined in contract tasks LP-1, LP-8 and LP-11, three integrated low pressure test series were conducted to demonstrate the CPU-400 pilot plant process controllability and combustion efficiency using manual control, semiautomatic control, and automatic computerized control methods. Task LP-1 defined a two-hour test using the horizontal combustor, inertial separator, and solid waste feed system developed under a previous contract. This test was conducted for the primary purposes of evaluating the combustion process controllability and characteristics of the fluidized bed and solid waste feed material. Task LP-8 defined a 24-hour test using the newly developed vertical combustor, aluminum removal vessel, and the intertial separator and the modified solid waste feed system. This test was conducted for the purposes of evaluating the combustion process controllability and efficiency, the characteristics of the fluidized bed material, and for determination of various combustor off-gas constituents. Task LP-11 defined a 48-hour test using the vertical combustor, aluminum removal vessel, two stages of inertial separators and the modified solid waste handling system. The testing performed during this test series essentially evaluated the same areas that were tested during the LP-8 testing, with the additional requirement that the entire process be conducted under automatic (computerized) control. All hardware and disciplines necessary for high pressure turbine testing were evaluated during the performance of these tests.

TASK LP-1 TESTING (16-SERIES TESTS)

Test Summary

Fluidized operation started at elapsed time ET=458.5 minutes. In the subsequent 340.5 minute period, numerous system adjustments and modifications were accomplished in preparation for the performance test interval. Included were two periods of blower shutdown totaling 87.5 minutes during which modifications were made to the twin pipe solid waste feed system. These alterations eliminated plugging problems at the airlock feeder valve (splitter at inlet section, and pocket discharge section). Also included was a period of bed makeup sand feeding (3500 pounds).

The continuous 2-hour period for performance analyses was initiated at ET=799 minutes and terminated at ET=919 minutes. The test was terminated at ET=941 minutes. Total consumption of solid waste was 11,972 pounds, a new record for a one day operation.

Test Objectives

The primary objective of the test series was to demonstrate the contollability of the hot gas system exhaust temperature produced by solid waste combustion. Specific test objectives are cited below:

1. Test duration: 2 hours continuous with no auxiliary fuel
2. Exhaust temperature: 1450° F ± 20° F
3. Combustion efficiency: 90 percent (minimum)

4. Superficial velocity: 7 feet per second
5. Measurement of weight and rate of solid waste feed
6. Measurement of calorific content of solid waste used
7. Measurement of moisture content of the solid waste
8. Measurement of correction factor for heat loss from the fluid bed

Test Setup and Hardware Description

The LP-1 test setup, shown schematically in Figure 5-1, consisted of the horizontal combustor, the multi-tube (6-inch diameter) inertial separator, and the solid waste handling system.

Hot Gas System-

The combustor system included a pneumatic (air) solid waste injection system, an auxiliary fuel (diesel oil) injection system, and a back flow bed heatup system. The gas from the fluid bed exhausted into the inertial particle separator. Downstream from the temperature sensing point, the gas was passed through a water spray section and then exhausted to the atmosphere. Details of the horizontal combustor and the other components which comprise the hot gas system have been previously described in Section III.

Control System-

The manual operation of the system was augmented with the analog control system shown in Figure 5-2. During this test, the test conductor retained an on-time option for direct control of the solid waste feed rates and bypass valve positions. The temperature of the cleaned gas leaving the inertial particle separator was the primary temperature to

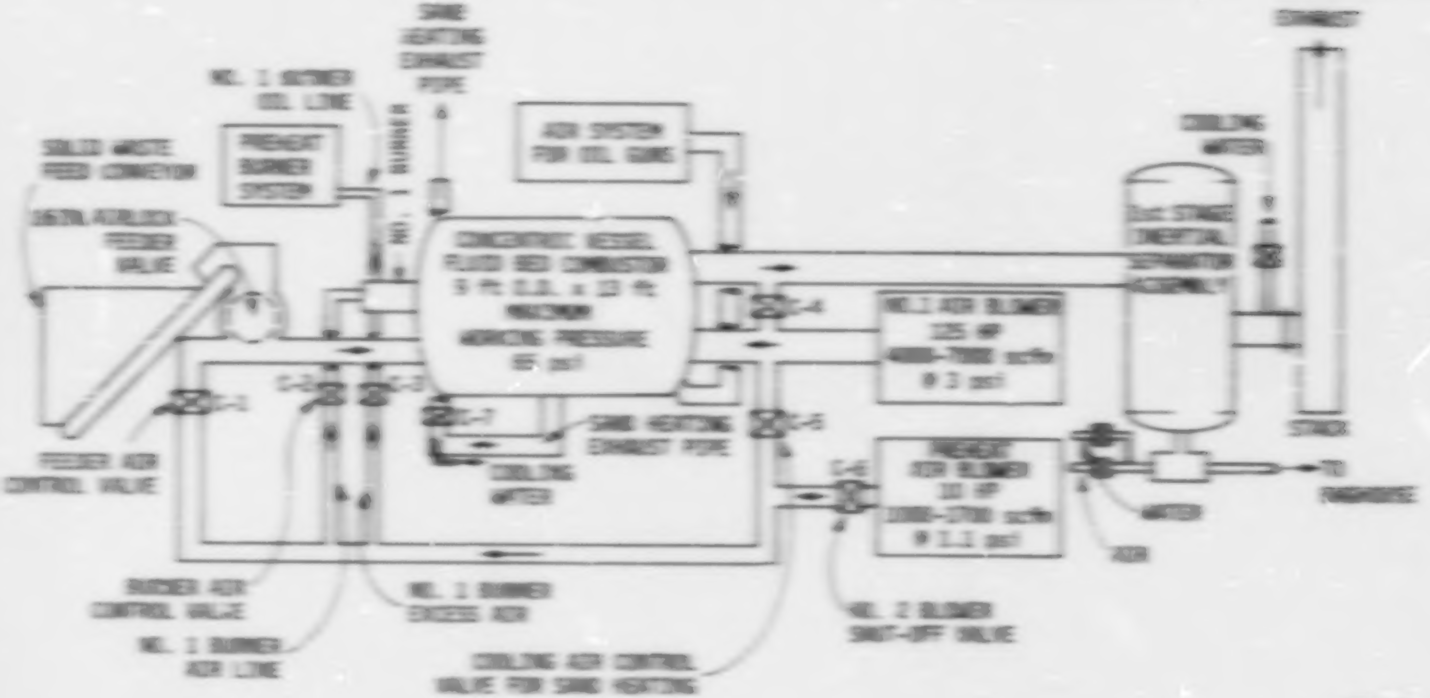

SAND HEATING EXHAUST PIPE
NO. 1 BURNER OIL LINE
PREHEAT BURNER SYSTEM
SOLID WASTE FEED CONVEYOR
ROTARY AIRLOCK FEEDER VALVE
NO. 1 BURNER
AIR SYSTEM FOR OIL GUNS
CONCENTRIC VESSEL FLUID BED COMBUSTOR 9 ft O.D. x 13 ft
MAXIMUM WORKING PRESSURE 65 psi
C-1
C-2
C-3
C-7
C-4
C-5
C-6
SAND HEATING EXHAUST PIPE
COOLING WATER
FEEDER AIR CONTROL VALVE
BURNER AIR CONTROL VALVE
NO. 1 BURNER EXCESS AIR
NO. 1 BURNER AIR LINE
COOLING AIR CONTROL VALVE FOR SAND HEATING
NO. 1 AIR BLOWER 125 HP 4000-7000 scfm @ 3 psi
PREHEAT AIR BLOWER 10 HP 1000-1700 scfm @ 1.1 psi
NO. 2 BLOWER SHUT-OFF VALVE
1st STAGE INERTIAL SEPARATOR ASSEMBLY
COOLING WATER
EXHAUST
STACK
WATER
AIR
TO BAGHOUSE
-221-39

Figure 5-1 LP-1 Test Setup

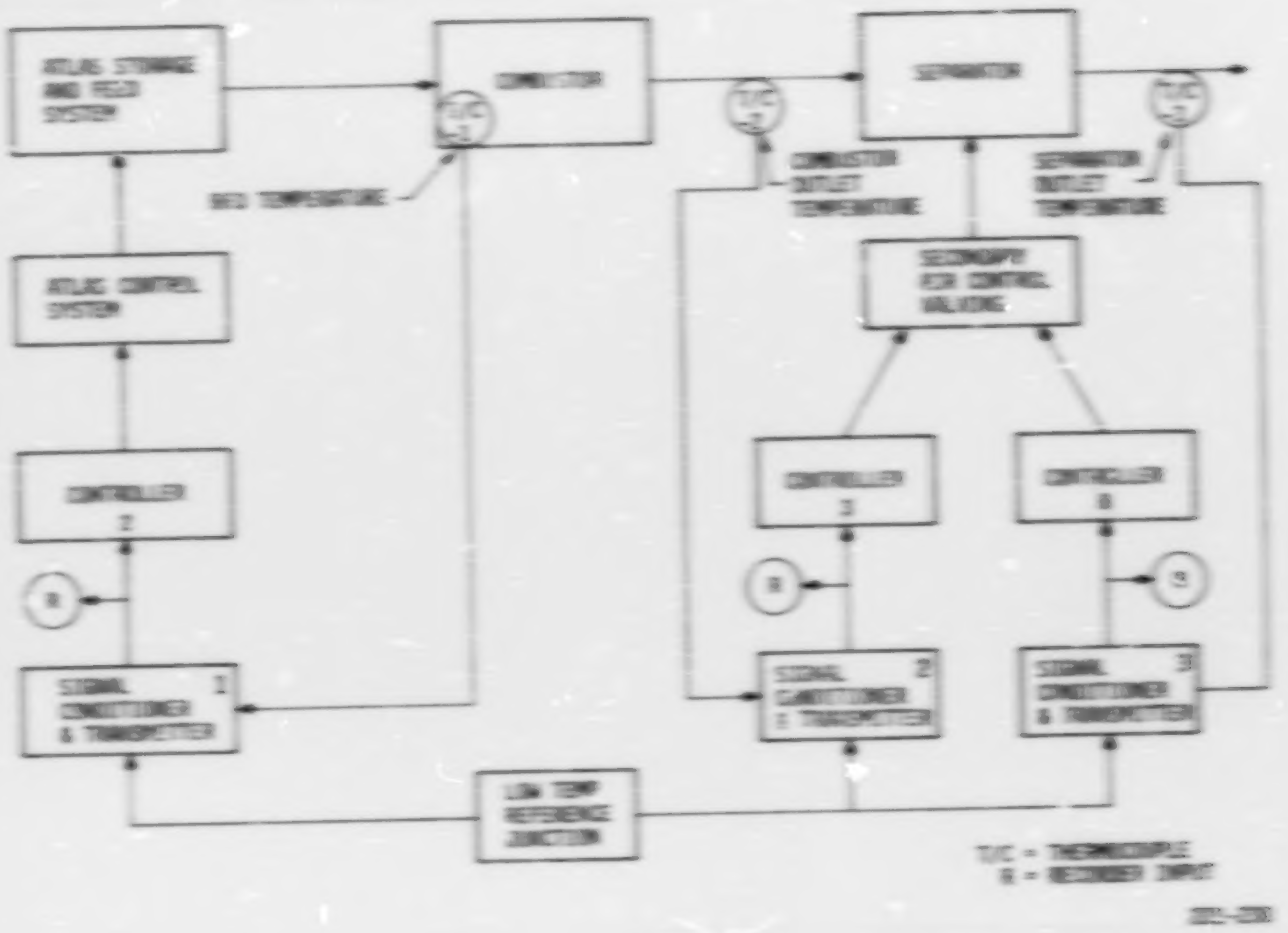

ATLAS STORAGE AND FEED SYSTEM
COMBUSTOR
SEPARATOR
T/C 1
T/C 2
T/C 3
FEED TEMPERATURE
COMBUSTOR OUTLET TEMPERATURE
SEPARATOR OUTLET TEMPERATURE
SECONDARY ECR CONTROL VALVING
ATLAS CONTROL SYSTEM
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
R
R
R
SIGNAL CONDITIONER & TRANSMITTER 1
SIGNAL CONDITIONER & TRANSMITTER 2
SIGNAL CONDITIONER & TRANSMITTER 3
LOW TEMP REFERENCE JUNCTION
T/C = THERMOCOUPLE
R = RECORDER INPUT
221-230

Figure 5-2 Control System, LP-1 Test

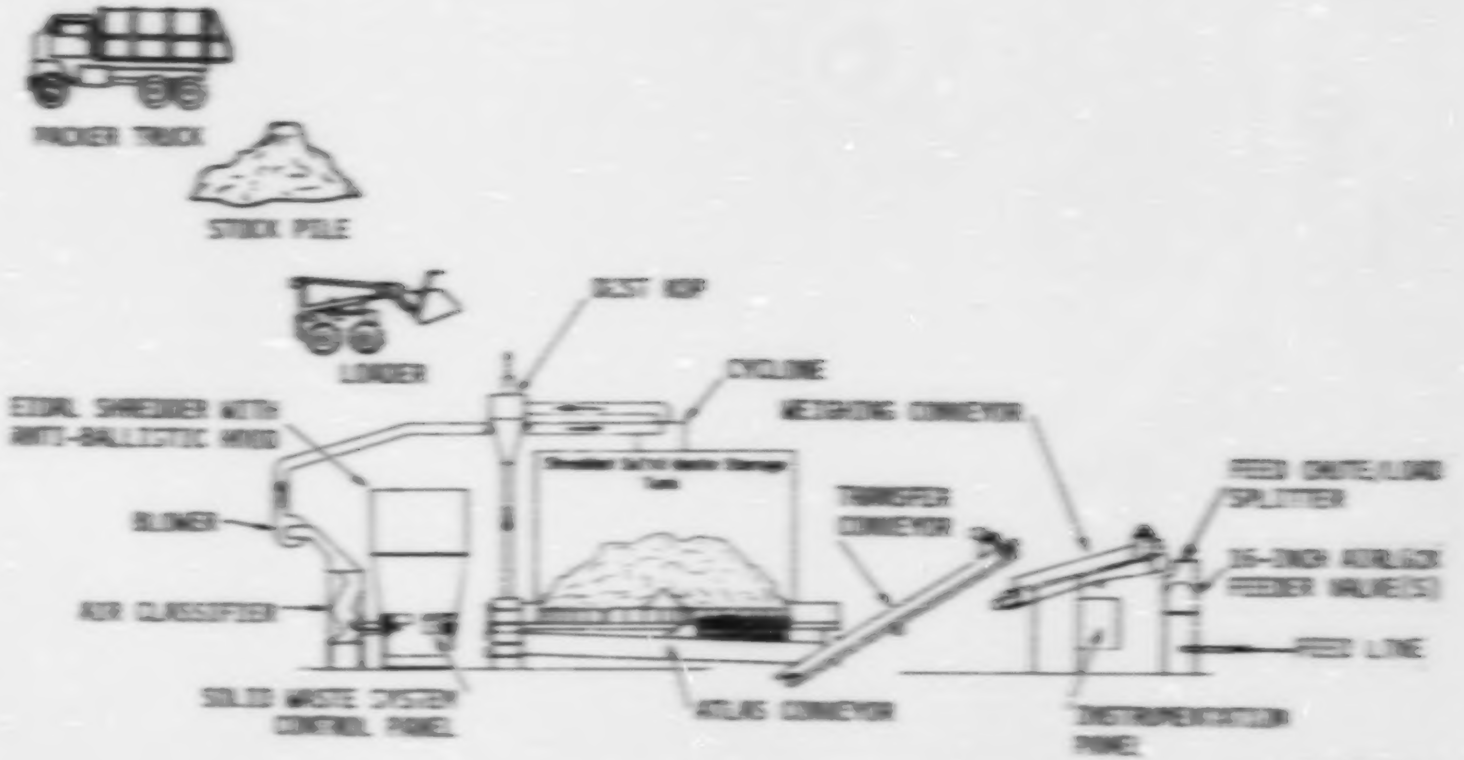
be controlled. The basic control technique utilized for this test was the maintenance of the fluid bed at a fixed temperature by modulating the fuel flow and controlling the hot gas system outlet temperature by controlling bypass air flow. Incorporated into the bypass air modulation was a control loop which anticipated changes to the hot gas system output temperature due to combustor outlet temperature variations.

Solid Waste Handling System-

The solid waste handling system (Figure 5-3) was developed under a previous contract and is described in detail in Appendix A. It consisted of two major subsystems: the shredder/air classifier/pneumatic transfer subsystem (Figure 5-4); and the Atlas storage/combustor feed subsystem (Figure 5-5). The shredder/air classifier equipment consisted of the 75 horsepower Eidal Mini-mill shredder, used to render a random lot of residential solid waste suitable for air transport into the fluid bed, and the CPC-designed close coupled air classifier, which was used to remove a large portion of the metal and glass from the solid waste.

From the air classifier, the shredded solid waste was transported to the Atlas storage and reclaim unit. Figure 5-5 shows the installation of the Atlas unit and the conveyors that meter the solid waste to the air-lock feeder valve as demanded by the control system.

The task of the air-lock feeder valve, Figure 5-6, is to transfer the solid waste from the ambient pressure zone of the conveyor to the pressurized solid waste feed pipe. A single 16-inch feeder valve configuration was used to insure an adequate supply and distribution of solid


PACKER TRUCK
STOCK PILE
LOADER
DUST HOP
CYCLONE
EDDAL SHREDDER WITH ANTI-BALLISTIC HOOD
Shredded Solid Waste Storage Tank
WEIGHING CONVEYOR
TRANSFER CONVEYOR
FEED CHUTE/LOAD SPLITTER
16-INCH ACRLOCK FEEDER VALVE(S)
FEED LINE
BLOWER
AIR CLASSIFIER
SOLID WASTE SYSTEM CONTROL PANEL
ATLAS CONVEYOR
INSTRUMENTATION PANEL

NOTE: FOR LP-8 TESTING -

(a) FEED CHUTE REPLACED BY LOAD SPLITTER

(b) SINGLE FEEDER VALVE AND 6-INCH FEED LINES
REPLACED BY TWO VALVES AND 5-INCH FEED LINES

Figure 5-3 Solid Waste Handling System (LP-1 and LP-8)

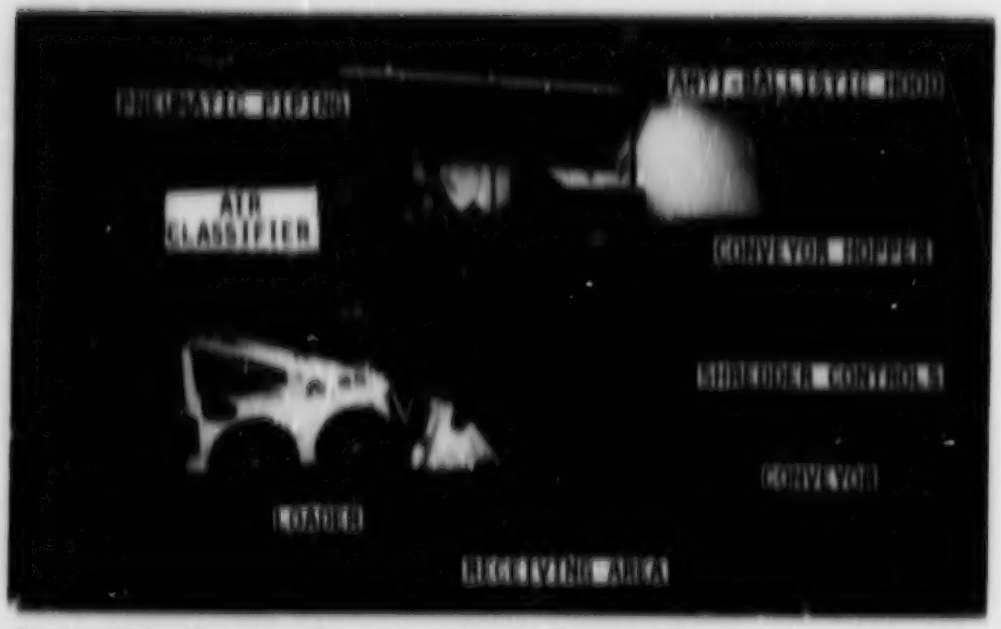

PNEUMATIC PIPING
ANTI-BALLISTIC HOOD
AIR CLASSIFIER
CONVEYOR HOPPER
SHREDDER CONTROLS
CONVEYOR
LOADER
RECEIVING AREA

Figure 5-4 Shredder/Air Classification/Pneumatic Transfer Subsystem

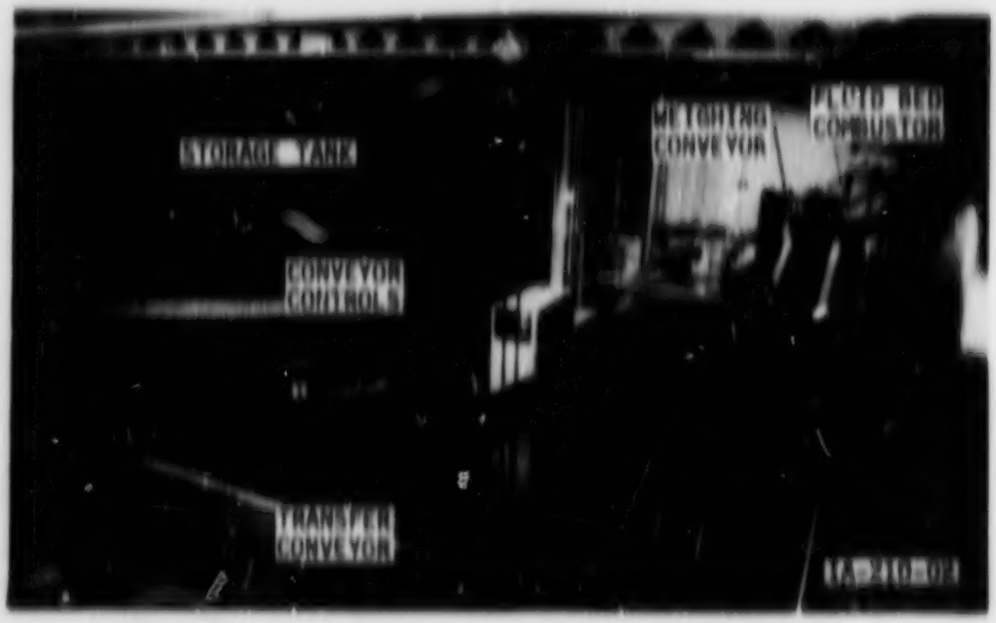

STORAGE TANK
WEIGHING CONVEYOR
FLUID BED COMBUSTOR
CONVEYOR CONTROLS
TRANSFER CONVEYOR
1A-210-08

Figure 5-5 LP-1 Atlas Storage/Combustor Feed Subsystem

16-INCH
FEEDER VALVE

Figure 5-6 16-Inch Air-lock Feeder Valve and Drive Assembly (LP-1) waste to the bed. This valve has a volume of 2.6 cubic feet and rotates at 11 rpm. During low pressure operation, the valve operated with 2 psi differential pressure. Two 5-inch diameter feed lines were used to carry the processed solid waste feed to the combustor.

Test Results

The bed was fluidized after 7½ hours of sand preheat time and the control conditions were initiated at a total elapsed time of 799 minutes. During the period between initial fluidization and start of the 2-hour performance test, modifications were made to the feeder valve to circumvent plugging problems at its internal splitter and lower discharge cavity.

Test Temperature Control-

Analog records of the key system temperatures, (Figure 5-7), show that the required test temperature of 1450° F ± 20° F was met for the separator exhaust during the 2-hour period between 799 and 919 minutes elapsed time. In addition to the analog temperature recordings, numerous temperatures were recorded with the digital data acquisition system. Air flow, solid waste feed rates, and pressure data were recorded and solid waste samples were taken at 15 minute intervals. Analysis of this data showed that the mean of the exhaust temperature differed from the setpoint by 2.7° F and the maximum standard deviation of the exhaust temperature was 6.9° F.

Superficial Velocity-

The superficial velocity through the fluid bed, based on air flow only,

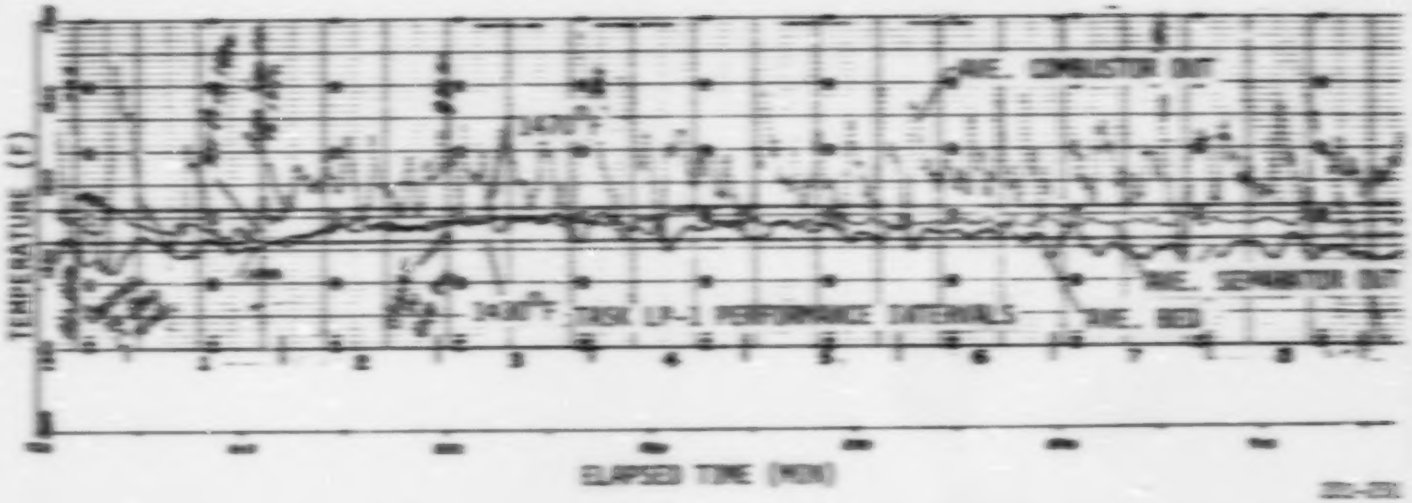


Figure 5-7 LP-1 Analog Record of Key System Temperatures

was 6 feet per second nominal with variations (depending on bypass air) of +0.1 to -0.6 feet per second.

Combustion Efficiency and Heat Loss.

Data and sample analysis results necessary for fuel heating value and combustion efficiency calculations are summarized in Table 5-1. The heat loss rate was based on temperature recordings of the combustor pressure shell, separator pressure shell and the interconnecting pipe between the vessels. The lower heating value (column J) was the Parr bomb calorimeter results corrected for the condensation of water vapor in the combustion products. The correction was based on a dry, inert-free combustible fraction based on $C_{30}H_{48}O_{19}$ composition. The correction was made to permit direct comparison (column K) of the Parr bomb caliber results to the heating value employed in the combustor heat balance calculations in which the vapor form of all the combustion products was used.

Post Test Inspection

The combustor was not disassembled immediately after the LP-1 test. Two problem evaluation tests were performed and a third was initiated when it was observed that poor bed fluidization was occurring.

When the combustor was opened for inspection it became evident that a clinker had formed on the fluidized bed surface. The amount of bed material in the bed area itself was reduced to about 50 percent, while significant amounts of sand and sand-glass agglomeration were found behind the active area and in the settling chambers. The big clinkers being formed on the bed surface consisted primarily of sand-glass

Table 5-1. LP-1 TEST SUMMARY OF FUEL HEATING VALUE RESULTS

	A	B	C	D	E	F	G	H	I	J	K
Rept. inter-val	Av. solid waste flow-rate (lb/min)	Moisture fraction	Inert fraction	Av. air flow-rate (lb/min)	Bed temperature range (°F)	Av. sepa-rator outlet temp. (°F)	Heat loss rate (Btu/min)	Computed heating value, Q_c (Btu/dry lb)	Heating value from calori-meter, Q_b (Btu/dry lb)	Lower heating value, Q_L (Btu/dry lb)	Combustion efficiency $100\ Q_c/Q_L$ (%)
1	24.81	0.311	0.088	290.8	1425 - 1435	1440	4271.3	6619.7	7254.0	6739.0	91.2
2	31.49	0.114	0.084	298.4	1435 - 1461	1446	4224.6	6413.2	6339.0	5821.6	110.2
3	30.13	0.301	0.129	299.3	1453 - 1460	1456	4244.1	6523.1	6573.1	6097.6	106.9
4	30.15	0.305	0.057	302.4	1443 - 1447	1448	4326.4	6574.1	7019.0	6477.5	101.5
5	31.59	0.286	0.054	302.6	1447 - 1449	1462	4269.2	6072.0	6862.4	6318.3	96.1
6	32.25	0.288	0.057	303.4	1443 - 1418	1462	4258.7	5871.6	6974.0	6431.3	91.3
7	27.25	0.277	0.144	304.5	1418 - 1433	1463	4222.1	6644.1	7190.1	6625.2	101.9
8	29.15	0.310	0.061	306.2	1403 - 1435	1463	4232.7	6507.2	6886.0	6316.2	109.1
								6461.5[a]		6359.0[a]	101.0[a]
								342.0[b]		255.6[b]	6.62[b]

[a] Mean

[b] Standard deviation

agglomerations which were brittle enough to be broken by hand; however, they proved to be firm enough not to be crushed by the bed action at 1300° F and 7 feet per second.

Investigation of the backheat history indicated that the final backheat was performed at a slightly higher temperature than the other tests (1780° F average and 1830° F peak) with used sand. The initial tests were at comparable levels, but these tests had new or low time sand in the bed. The phenomena that is believed to have occurred is that since the sand was well used, it had an increased amount of glass which has a lower softening point than new sand (about 1500° F to 1550° F versus 2200° F); the level of backheat was enough to cause bed agglomeration which was sufficient to build up a crust on the bed surface that could not be broken down by bed action.

The baghouse was inspected and filter bags were found to have failed. The puffback hand valve was jammed with sand and stalled the puffback drive. This allowed the bags to load up and fail since they were not being periodically cleaned.

An inspection of the inertial separator tubes after a total of 735 minutes of fluidized operation revealed that 15 tubes were plugged and 6 tubes were partially plugged.

The ash hopper under the inertial tubes was found to be almost completely filled. Apparently the ash transport system was overloaded. This was not surprising as the horizontal combustor experiences high elutriation and, therefore, the inertial separator was experiencing a high ash/sand loading.

Conclusions

The following conclusions can be drawn from the LP-1 test series:

1. The process of combusting solid waste in a fluid bed combustor can be maintained within a controlled temperature band such as 1460° F to 1470° F. This should allow the use of this type of combustor in a gas turbine system.
2. The performance of the inertial separator system was unsatisfactory in this test series because of tube plugging. The reason for this is believed to be insufficient velocities in the tubes.
3. The backheat temperatures for aged sand beds should be at more moderate levels (below 1500° F) than were used in this series. This should prevent sintering of the ash in the bed during bed heatup.
4. The combustion efficiency indicated by the combustibles analyzer was greater than 98 percent. This is in agreement with the combustion efficiency from heat balance which also indicated high efficiency.
5. Testing conducted with the horizontal combustor demonstrated that a combustor with high freeboard volume is necessary to reduce bed elutriation. In addition, the combustor must reduce the tendency of the feeding air flow to direct sand particles toward the exhaust port where they are entrained into the exhaust gas stream and carried out of the combustor.
6. An alumina/sand separator should be added to the hot gas subsystem between the fluid bed combustor and the first stage inertial separator

to reduce the high solids input to the first stage inertial separator.

7. The solid waste handling system performed moderately well during this test series, however some feed system jamming occurred during periods of high volume demands.

TASK LP-8 TESTING (18-SERIES TESTS)

Test Summary

Fluidized operation started at elapsed time ET=140 minutes, after a sand heating period of 121 minutes. Oil combustion was utilized to bring the bed to the desired temperature for solid waste combustion. One stop occurred during this time because of the loss of the facility air supply. At ET=223 minutes solid waste combustion was started and continued until ET=2428 minutes with three interruptions. These interruptions occurred at ET=310, 629, and 934 minutes and were caused by plugging in the feed line on two occasions and in the feeder valve outlet on the other occasion. The 24-hour control period commenced at ET=988 minutes and terminated at ET=2428 minutes. At ET=2063 minutes the feed line under feeder valve no. 2 plugged; the last portion of the 24-hour control period was completed on one feed line.

A period of 24 hours was completed with exhaust temperature controlled to within 1460° F ± 30° F and 9.75 hours with the temperature controlled to within 1460° F ± 20° F. Only solid waste was used as a fuel during the 24-hour control period and automated solid waste feed was used. During the 34.83 hour solid waste burn time 69,134 pounds were consumed.

Bed depth increased 1 inch during the test; no bed material was added or removed for bed maintenance.

Test Objectives

The primary objective of this test series was to demonstrate the process controllability and efficiency using semiautomatic control techniques. Specific test objectives are cited below:

1. Test duration: 24 hours continuous
2. Exhaust temperature: 6 hour span, 1450° F ± 20° F
   24 hour span, 1450° F ± 30° F
3. Combustion efficiency: 95 percent (two methods)
4. Residue removal: drain to maintain 35 ± 3.5 IW bed ΔP
5. Fluid bed: maintain weight within ± 10 percent (by ΔP) <4 percent elutriation per hour (>30 mesh)
6. Mass accounting of sand and inert material
7. Exhaust gas: determine percentage of the following chemical compounds: CO, CO_2, CH_4, HCl, and NO_x
8. Particulate: determine particulate loading of exhaust gas
9. Superficial velocity: 4 to 8 feet per second
10. Post-test bed inspection for clinkers (none >2 inches)

Test Setup and Hardware Description

The LP-8 test setup, shown schematically in Figure 5-8, consisted of the newly developed vertical combustor and alumina separator, the modified inertial separator used during previous tests and the modified solid waste handling system.

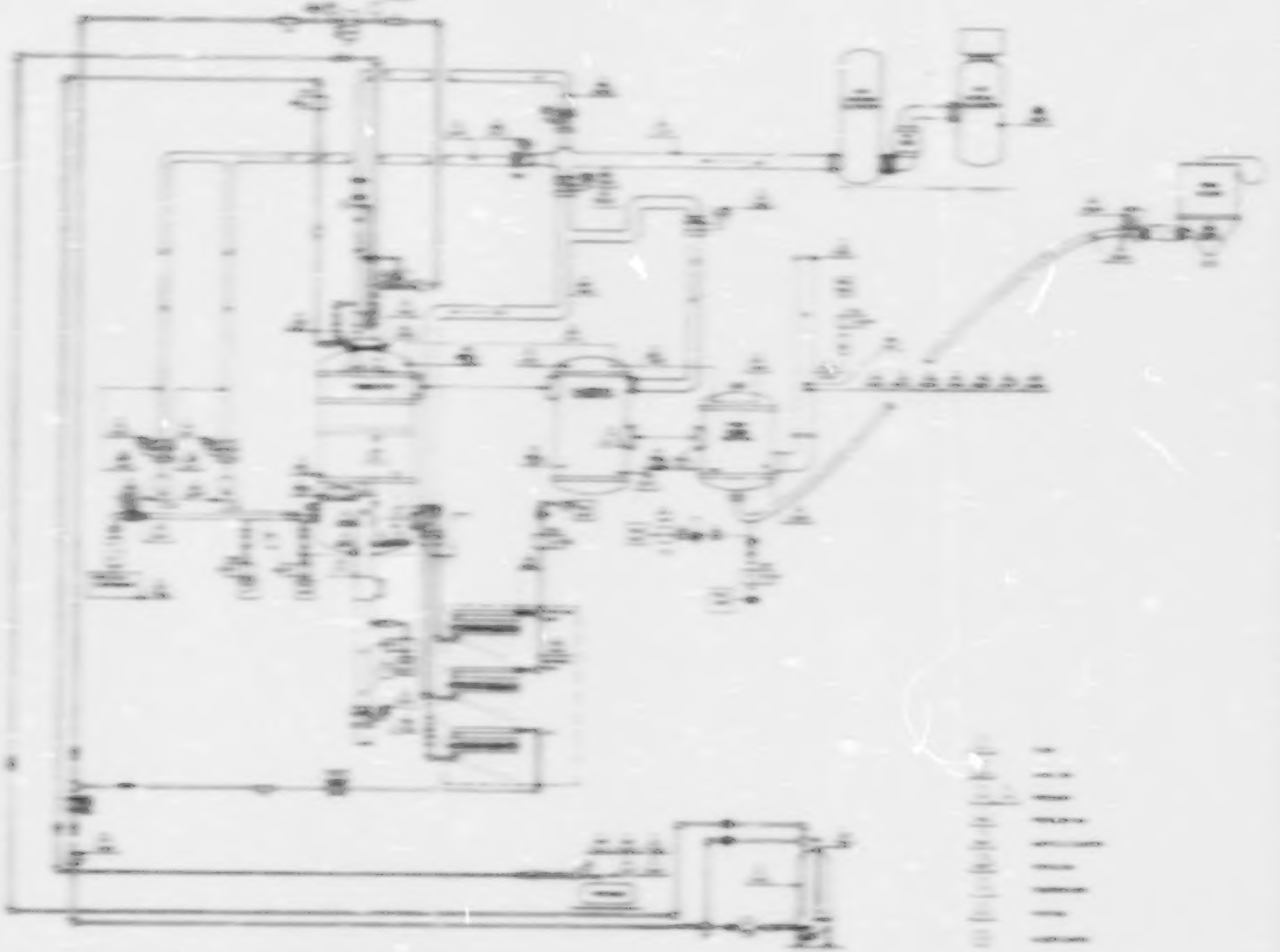


Figure 5-8 LP-8 Test Setup

Hot Gas System-

The vertical combustor system included a pneumatic solid waste injection system, an auxiliary fuel injection system, and a back flow bed heatup system. The gas from the fluid bed was exhausted into the alumina separator (first stage separator) which de-entrained the larger particles from the gas stream, and was then routed to the inertial separator (second stage separator) for final cleanup of the exhaust gas. Downstream from the temperature sensing point, at the second stage separator outlet, the gas was passed through a water spray section and then exhausted to the atmosphere. Residue from the second stage separator was pneumatically transported to a baghouse filter. The combustor and particle separators are shown in Figure 5-9. Details of this equipment and the remaining equipment elements that comprise the hot gas system have been previously described in Section III. The modifications made to the inertial separator since the completion of the LP-1 testing series are cited below:

1. The original reverse flow cyclone tubes configuration was changed to the "reduced cone angle" tube configuration shown in Figure 3-17(c).
2. Only 24 of the 48 cyclone tubes were used. See Figure 3-22 for the tube arrangement.
3. The outlets of the non-active tubes were removed to provide better flow manifolding to the active tubes and the resultant holes were plugged with special seal adapters.
4. A baffle plate was welded to the top of the torroidal manifold at the inlet area to avoid possible high flow and high particle loading in tubes adjacent to the inlet connection.

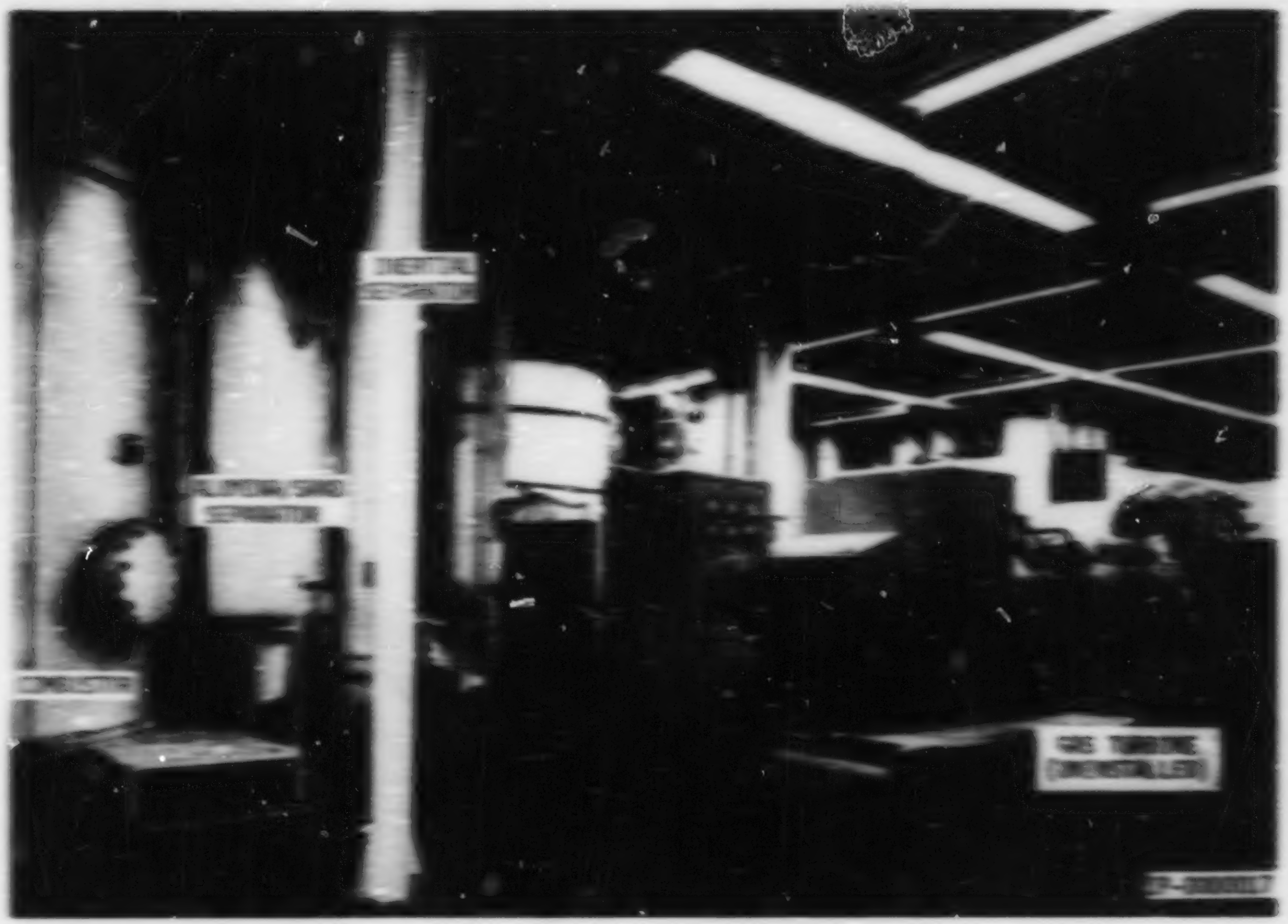

INERTIAL SEPARATOR
ALUMINA/SAND SEPARATOR
COMBUSTOR
GAS TURBINE (UNINSTALLED)

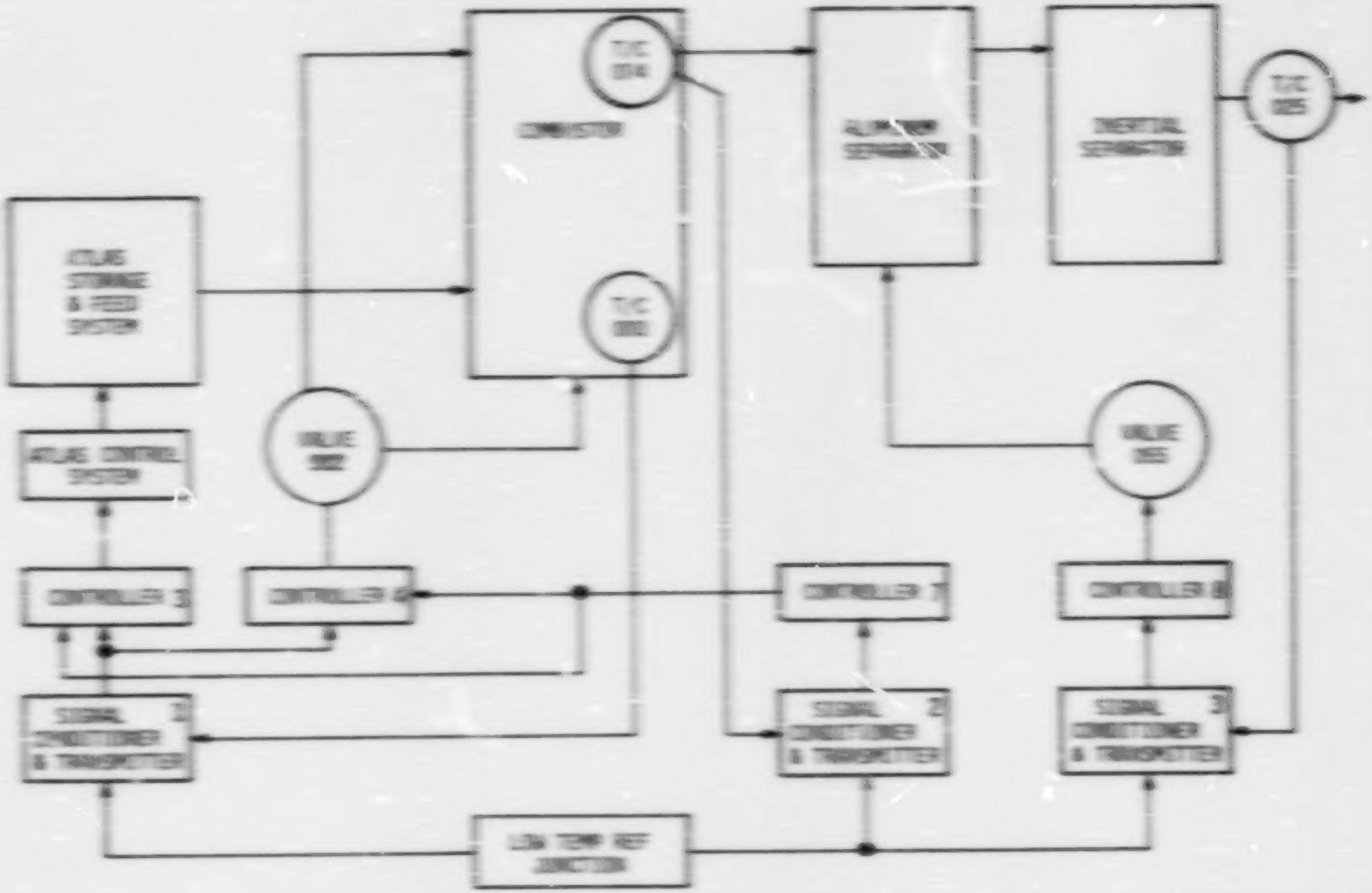
Figure 5-8 LP-8 Combustor and Particle Separator Configuration

Control System -

The temperature of the cleaned gas leaving the second stage separator was the primary temperature to be controlled. The basic control technique utilized for this test was the controlling of the fluid bed temperature by modulating the fuel flow; and controlling the hot gas system outlet temperature by changing bypass air flow around the first and second stage separators. Incorporated into the bypass air modulation was a sub-loop which anticipated changes to the hot gas system output temperature due to combustor outlet temperature variations. During the test, the test conductor retained an on-time option for direct control of the solid waste feed rates and bypass valve positions. A simplified block diagram of the control system is presented in Figure 5-10. This diagram includes only the primary active elements of the test. Start up, secondary, and inactive sections of the system have been omitted for clarity. Refer to Section IV for a summary of the LP-8 control system. The temperature, pressure and flow sensors that were used to control, monitor and analyze the pilot plant operation during the 24-hour test period are shown in Figure 5-8 and are described in Tables 5-2 and 5-3. Fisher controller settings are shown in Table 5-4.

Solid Waste Handling System-

The LP-8 solid waste handling system (Figure 5-3) was modified to improve the control of the solid waste feed rate and to reduce jamming tendencies. These changes were made to the Atlas storage/combustor feed subsystem (Figure 5-11) and did not affect the shreeder/ air classifier/


ATLAS STORAGE & FEED SYSTEM
ATLAS CONTROL SYSTEM
COMBUSTOR
T/C 004
T/C 001
VALVE 002
ALUMINUM SEPARATOR
INERTIAL SEPARATOR
T/C 025
VALVE 055
CONTROLLER 3
CONTROLLER 4
CONTROLLER 7
CONTROLLER 8
SIGNAL CONDITIONER & TRANSMITTER 1
SIGNAL CONDITIONER & TRANSMITTER 2
SIGNAL CONDITIONER & TRANSMITTER 3
LOW TEMP REF JUNCTION

5-10 LP-8 Simplified Control Loop Block Diagram

Table 6-2. LP-8 TEMPERATURE SENSORS

T/C[a] I.D.	Measurement	Use
000	Fluid bed 9"	Solid waste feed
001	Fluid bed 9"	Control & bed operation
002	Fluid bed 9"	
003	Fluid bed 9"	
004	Fluid bed 9"	
005	Fluid bed 9"	
006	Combustor plenum 9"	Backheat control
007	Combustor plenum 9"	
008	Distributor plate surface	
009	Distributor plate surface	
010	Fluid bed 9"	
011	Aluminum vessel outlet	Mix air control
014[b]	Freeboard 10"	Bed set point adjustment
015	Freeboard 10"	
016	Combustor wall just below feedline surface	Heat loss
017	Combustor dome - surface	
018	Diesel oil supply - 1"	Over temp
019	Aluminum vessel wall - surface	
020	1st stage inertial separator top dome - surface	Heat loss
021	1st stage inertial separator wall - side - surface	
024	1st stage inertial separator material removal line between water injection point and valve 009 - surface	Ash flow
025[b]	1st stage separator outlet gas-1"	Mixed air control
026	1st stage separator outlet pipe - surface	
037	L. P. compressor outlet gas - 1"	Flow calc.

[a] Dimensions associated with each T/C indicate length that the T/C projects into the associated area. When "surface" is noted, the T/C is tack welded to the noted surface.

[b] Control thermocouples

Table 5-3. LP-8 PRESSURE AND FUEL FLOW SENSORS

Sensor I.D.	Measurement	Use
101	Solid waste comb plenum press.	Superficial velocity calc.
107	Compressor outlet	
120	Bed diff. pressure	Fluidization and bed height monitoring
121	Distr. plate diff. press.	Distr. plate status monitoring
123	1st inertial stage sep. press. drop	Separator status monitoring
124	1st inertial stage sep. outlet press.	Sep. status monitoring
125	Alumina separator press. drop	Sep. status monitoring
140	Feedline 1 air flow sensor diff. press.	Feedline 1 air control and
141	Feedline 2 air flow sensor diff. press	Feedline 2 air control and
146	Solid waste comb. air flow	Fluidizing air flow determination
147	Backheat burner air flow	Backheat control & calculation
160	Diesel fuel flow rate to solid waste comb.	Diesel fuel control & energy bal. calc.

Table 5-4. LP-8 FISHER CONTROLLER SETTING

Controlled parameter	Fisher Controller							
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7[a]	No. 8
PB %	100	100	50	100	50	50	70	75
Reset	10	0.1	0.05	0.5	0.1	0.1	0.1	3.5
Range	x1	x1	x10	x1	x1	x1	x10	x1
Control action	Direct	Reverse	Reverse	Reverse	Direct	Direct	Reverse	Reverse
Rate	-	0	0	0.75	-	0	-	-
Controlled element	Valve 005	Valve 007	Valve 002	Atlas[a] control system	Valve 000	Valve 001	Fisher #3 or #4[a]	Valve 055 by-pass valve
Controlled variable	Damp air	Backheat flow	Oil flow	Solid waste feed	#1 feed-line air flow	#2 feed-line air flow	Fisher set point	Exhaust mixing air

[a] Cascaded with Controller #3 for fuel oil feed control or with Controller #4 for solid waste feed control.

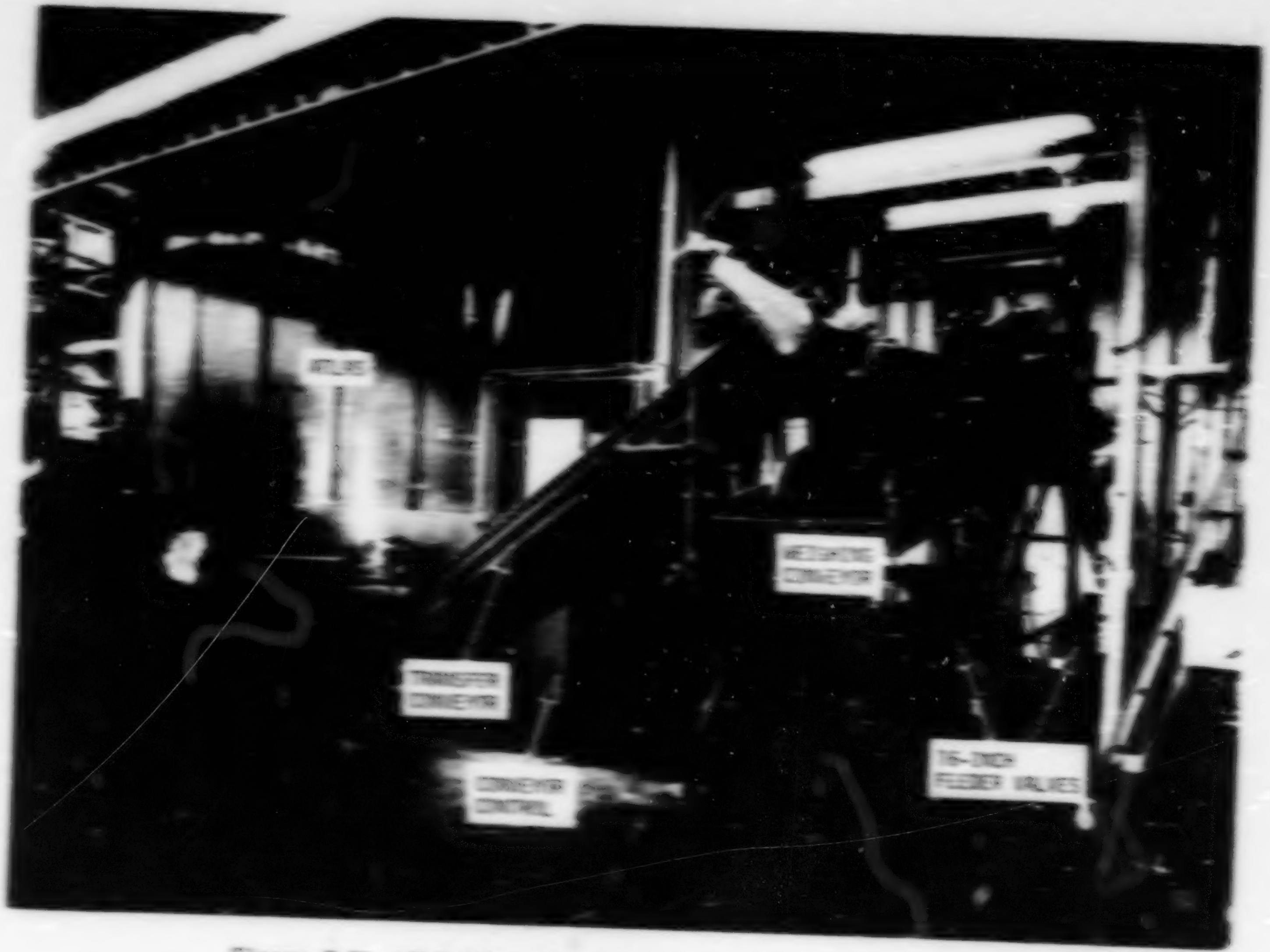

ATLAS
TRANSFER CONVEYOR
CONVEYOR CONTROL
WEIGHING CONVEYOR
16-INCH FEEDER VALVES

Figure 5-11 JP-8 Atlas Storage and Combustor Feed Subsystem

pneumatic transfer subsystem (Figure 5-4). Refer to Appendix A for complete details of the solid waste handling system. Specific changes implemented for the LP-6 test series are itemized below:

1. The Atlas circumcylone inlet, which produced unsymmetrical distribution and localized compacting of fuel, was replaced by a flat, splatter plate which evenly distributed fuel over the Atlas floor.
2. The efficiency of the Atlas sweeps were improved by adding an extra bucket to each chain and incorporating digger spikes.
3. The diversion of dust collector reject back into the Atlas was implemented by the addition of a rotary feeder.
4. A "clod buster" was added to the outfeed conveyor to break up composted solid waste.
5. Load levelers were incorporated on the transfer and weigh conveyors to provide a constant volume of fuel per foot of conveyor.
6. The speeds of the transfer and weighing conveyors were synchronized with the Atlas conveyor sweep speed by a common variable frequency controller which was controlled by the commanded volume signal sent to the Atlas control system.
7. The single feeder valve installation was replaced by two CPC-designed 16-inch feeder valves. Each valve had a volumetric capacity of 2.6 cubic feet per second and fed a separate 5-inch diameter combustor inlet feed pipe.
8. The steel pant-leg chute which fed the feeder valve during previous testing was replaced by a load splitter.

Test Results and Analysis

Exhaust Temperature-

Figure 5-12 shows inertial separator outlet temperature during the 24-hour control period. The 24-hour and 6-hour temperature bands of 1450 ± 30° F and 1450 ± 20° F respectively, have been superimposed. Control within the required temperature limits is apparent from Figure 5-12. A statistical analysis was performed on the 287 separator outlet temperature readings from the data acquisition system. This analysis yielded the following results:

Mean	1456° F
Variance	58.2° F
Standard Deviation	7.6° F

The results show the mean differing from the nominal point by 6° F and the standard deviation indicating a ± 3σ value of ± 22.8° F assuming a a normally distributed population of data.

Examination of the continuous recording of inertial separator outlet temperature confirms that temperature was continuously controlled within the specified limits.

Combustion Efficiency-

Heat Balance Technique - Combustion efficiency calculated by the heat balance technique is presented in Table 5-5. These calculations utilize the laboratory results for solid waste moisture fraction and inert fraction (see columns B and C, Table 5-5). These results indicated an average computed heating value of 7934.5 Btu/lb of combustibles

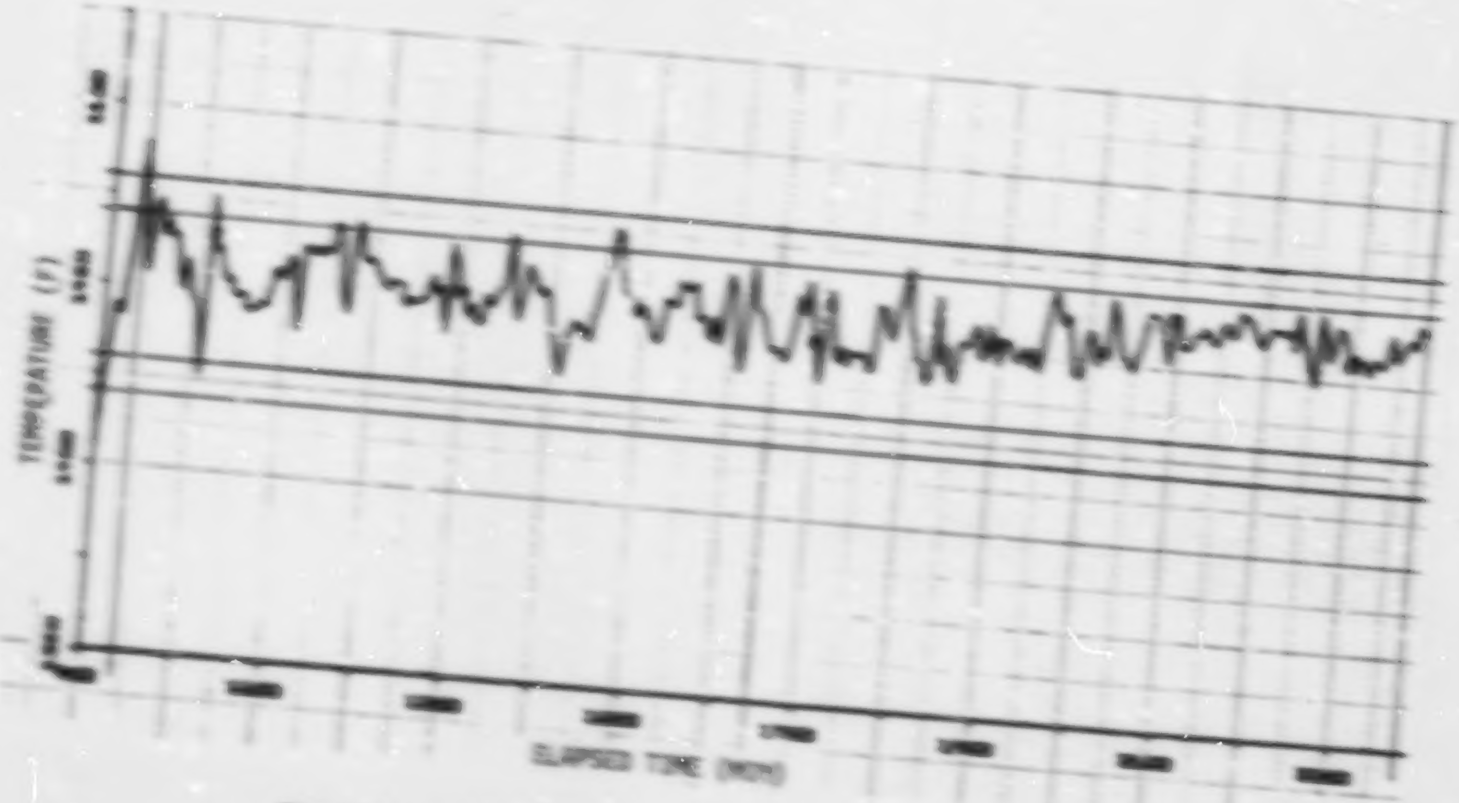


Figure 5-37 LP-8 Second Stage Separator Exhaust Temperature [illegible]

Table 5-5. LP-8 COMBUSTION EFFICIENCY RESULTS, HEAT BALANCE TECHNIQUE

	A	B	C	D	E	F	G	H	I	J	K
Test interval	Av. solid waste flow rate (lb/min)	Moisture fraction	Inert fraction (lb/lb wet)	Av. air flow rate (lb/min)	Bed temperature range (°F)	Av. T.. generator outlet temp. (°F)	Heat loss rate (Btu/min)	Corrected heating value, Q_c (Btu/lb comb.)	Heating value from calorimeter, Q_h (Btu/dry lb)	Lower heating value, Q_L (Btu/lb comb.)	Combustion efficiency 100 Q_c/Q_L (%)
1	34.76	.3011	.1160	312.7	1350 – 1357	1532.6	6070	7707.2	7233.6	8069.2	95.51
2	35.07	.2823	.1230	312.7	1357 – 1352	1371.6	7562	8605.5	7051.8	8106.2	107.1
3	36.60	.3158	.2004	312.7	1352 – 1360	[illegible]	6900	6979.0	7315.4	7907.0	88.26
4	36.81	.3027	.1165	312.7	1350 – 1376	1507.1	6501	7049.5	7152.2	7952.3	88.66
5	29.25	.3550	.1408	312.7	1376 – 1352	1552.4	5702	7375.7	7264.9	8467.3	87.11
6	34.29	.2643	.1026	312.7	1352 – 1353	1489.1	5940	9137.2	6542.1	8255.0	110.7
7	33.04	.2596	.1091	312.7	1353 – 1360	1494.5	5756	8389.8	6626.0	8432.0	99.40
8	32.71	.2947	.1081	312.7	1360 – 1330	1491.1	5902	8540.1	6430.9	8151.2	104.8
9	32.60	.3007	.1136	312.7	1330 – 1275	1485.1	6061	7883.1	6751.9	7960.2	98.91
10	35.35	.3031	.1302	257.1	1275 – 1276	1514.8	5211	8097.7	6805.5	7731.0	104.6
11	27.92	.2351	.1263	257.1	1276 – 1275	1512.6	5485	8175.9	7141.6	8179.2	99.97
12	28.72	.2857	.1214	257.1	1275 – 1300	1519.6	5340	7180.7	7010.8	7806.7	92.03
								7934.5[a]		8066.6[a]	98.08[a]
								664.15[b]		229.25[b]	7.082[b]

[a] Mean

[b] Standard deviation

while the bomb calorimeter indicates 8086.6 Btu/lb. This yields an average combustion efficiency of 98.09 percent.

Because of the disparity in the inerts mass accounting, it is believed that the solid waste sample used in laboratory tests were not representative of the solid waste consumed. Table 5-6 presents combustion efficiency calculated using an average inerts fraction of 0.183 obtained from the inerts mass accounting. Moisture fraction was also adjusted assuming the missed portion of inerts contained insignificant moisture. Results of this adjustment in inerts content raise the average calculated heating value to 8298.4 Btu/lb of combustibles. Although inerts disparity affects the heating value per dry pound, it does not affect the heating value per combustible pound which makes the bomb calorimeter test results for the lower heating value (column J, Table 5-6) valid even for erroneous inerts content.

Carbon Combustion Technique- The results from the carbon combustion efficiency calculations are summarized in Table 5-7. In this method it is assumed that unburned carbon in the flue gas will exist in the forms of CO, HC (hydrocarbons), and C (elemental carbon) only. Therefore, combustion efficiency can be calculated by the following equation:

$$\eta = \frac{\frac{12}{44} a \, (\Delta H_{CO_2}) + \frac{12}{28} b \, (\Delta H_{CO}) + \frac{24}{30} c \, (\Delta H_{HC})}{\left(\frac{12}{44} a + \frac{12}{28} b + \frac{24}{30} c + d\right) \Delta H_{CO_2}}$$

Table 5-6. LP-8 COMBUSTION EFFICIENCY RESULTS, MASS BALANCE TECHNIQUE

	A	B	C	D	E	F	G	H	I	J	K
Test interval	Av. solid waste flow-rate (lb/min)	Moisture fraction	Inert fraction (incl. ash)	Av. air flow-rate (lb/min)	Bed temperature range (°F)	Av. af. separator outlet temp. (°F)	Heat loss rate (Btu/min)	Computed heating value, Q, (Btu/lb comb.)	Heating^a value from calorimeter, Q, (Btu/dry lb)	1-run heating value, Q, (Btu/lb dma)	Combustion efficiency 100 Q/Q (%)
1	34.76	.2509	.1830	312.7	1356 – 1357	1517.6	8051	8249.8	7225.6	8083.0	102.2
2	35.97	.2582	"	312.7	1357 – 1352	1505.6	7567	9211.3	7803.8	8136.0	113.2
3	38.60	.2803	"	312.7	1352 – 1350	1504.1	6999	7560.7	7315.4	7907.0	95.62
4	36.81	.2808	"	312.7	1350 – 1376	1521.3	6485	7530.1	7152.2	7952.1	94.70
5	36.29	.2906	"	312.7	1376 – 1352	1527.4	5774	7705.0	7154.5	8467.1	91.00
6	38.29	.2506	"	312.7	1352 – 1353	1499.3	5935	9359.9	7848.1	8255.0	113.3
7	33.84	.2808	"	312.7	1353 – 1360	1498.5	5757	8234.4	6826.8	8612.6	95.61
8	32.70	.2957	"	312.7	1360 – 1330	1499.1	5884	8866.7	6429.9	8052.2	110.1
9	28.60	.2905	"	312.7	1330 – 1275	1496.1	6040	8834.9	6953.3	7900.2	111.9
10	26.36	.2902	"	257.1	1275 – 1276	1510.8	5203	8524.8	6806.5	7711.0	110.5
11	27.92	.3145	"	257.1	1276 – 1275	1512.6	5444	8688.5	7143.6	8178.2	106.1
12	28.72	.2946	"	257.1	1275 – 1300	1511.6	5337	7625.5	7032.8	7856.7	97.08
								8298.4^b		8085.6^b	102.6^b
								600.60^c		330.25^c	7.340^c

^a Values reproduced from Table 5-6.
^b Mean
^c Standard deviation

Table 5-7. LP-8 COMBUSTION EFFICIENCY RESULTS, CARBON COMBUSTION TECHNIQUE

Performance interval	Wt. fraction of CO_2 (%)	Wt. fraction of CO (%)	Wt. fraction of CH_x (%)	Wt. ratio of C	Combustion efficiency (%)
1	10.32	2.607×10^{-3}	$.7034\times10^{-3}$	42.90×10^{-6}	99.80
2	9.862	2.607×10^{-3}	1.045×10^{-3}	42.40×10^{-6}	99.79
3	10.32	2.607×10^{-3}	1.396×10^{-3}	45.91×10^{-6}	99.77
4	10.32	3.910×10^{-3}	1.748×10^{-3}	42.90×10^{-6}	99.76
5	10.32	3.910×10^{-3}	1.541×10^{-3}	42.90×10^{-6}	99.77
6	10.32	5.223×10^{-3}	1.396×10^{-3}	41.40×10^{-6}	99.76
7	10.32	3.910×10^{-3}	1.748×10^{-3}	43.40×10^{-6}	99.76
8	10.32	3.910×10^{-3}	1.541×10^{-3}	43.40×10^{-6}	99.76
9	10.32	2.607×10^{-3}	1.748×10^{-3}	$40.90\times1-^{-6}$	99.78
10	10.32	3.910×10^{-3}	1.748×10^{-3}	55.29×10^{-6}	99.72
11	10.32	5.223×10^{-3}	1.541×10^{-3}	52.34×10^{-6}	99.72
12	10.92	7.830×10^{-3}	1.748×10^{-3}	55.48×10^{-6}	99.69
					99.76[a]
					0.0317[b]

[a] Mean

[b] Standard deviation

where: a = weight concentration of CO_2 in flue gas

b = weight concentration of CO in flue gas

c = weight concentration of HC in flue gas

d = weight ratio of C to flue gas

The CO_2, CO, and CH_x measurements (columns A, B, and C in Table 5-7) were obtained from the online gas analysis equipment. The free carbon (column D in Table 5-7) was based on laboratory analysis of samples from the first stage separator and baghouse. One sample was obtained from the aluminum separator after the test while twelve samples were obtained of the baghouse flyash during the test. As indicated in Table 5-7, this method indicates high combustion efficiency (column E in Table 5-7) with an average value of 99.76 percent.

Both this method and the heat balance technique indicate high combustion efficiency. It can therefore be stated that the system has demonstrated combustion efficiency in excess of the 95 percent required in the test plan.

Material Accounting-

A mass balance was conducted on the inert portion of the solid waste fuel. The material caught in the vessels and exhausted through the stacks is tabulated in Table 5-8. The bed weight increase was calculated by using an initial height of 24 inches and a final height of 25 inches and a density of 90 pounds per cubic foot. The material gathered in the separator and baghouse was removed and weighed. The material exhausted out the main stack was calculated from the measured particle loadings. The

Table 5-8. LP-6 INERT/ASH MATERIAL ACCOUNTING

Parameter	(lbs)
Bed growth	292
Aluminum tank sand/ash	8760
Aluminum tank hard clinker	132
Flyash in inertial separator	783
Hard clinker in inertial separator	23
Flyash out main exhaust	321
Flyash in baghouse hopper	2224
Flyash out baghouse exhaust	107
Total	12,642

material exhausted from the baghouse was estimated from visual comparison of the baghouse and main exhaust.

The total amount of inert ash material input to the system was estimated from the average inert fraction of the 12 solid waste samples taken during the 24-hour control period. The average inert fracion thus determined was 0.137; this figure times the 69,134 pounds of solid waste consumed yields an estimated inert material input of 9470 pounds.

The reason for the large variation in the calculated and measured inerts input is probably due to nonrepresentative solid waste samples. The solid waste samples were taken from the transfer conveyor and it is probable that a large portion of the inerts were on the belt and did not get sampled. The average inert fraction calculated from the accounting balance was 0.183.

Bed Maintenance-

The bed weight was maintained within the required ± 10 percent. The initial bed weight was estimated at 7408 pounds and the final weight measured at 7700 pounds, which is an increase of 3.94 percent. This degree of bed maintenance is verified by the bed pressure drop measurement presented in Figure 5-13. This figure shows bed differential pressure remaining almost constant until ET = 2063 minutes when a gradual increase started due to one feed pipe operation. This is due to the reduced combustor air flow when one feed pipe was shut down. No sand was added to the bed nor was any bed material removed by the bed maintenance system.

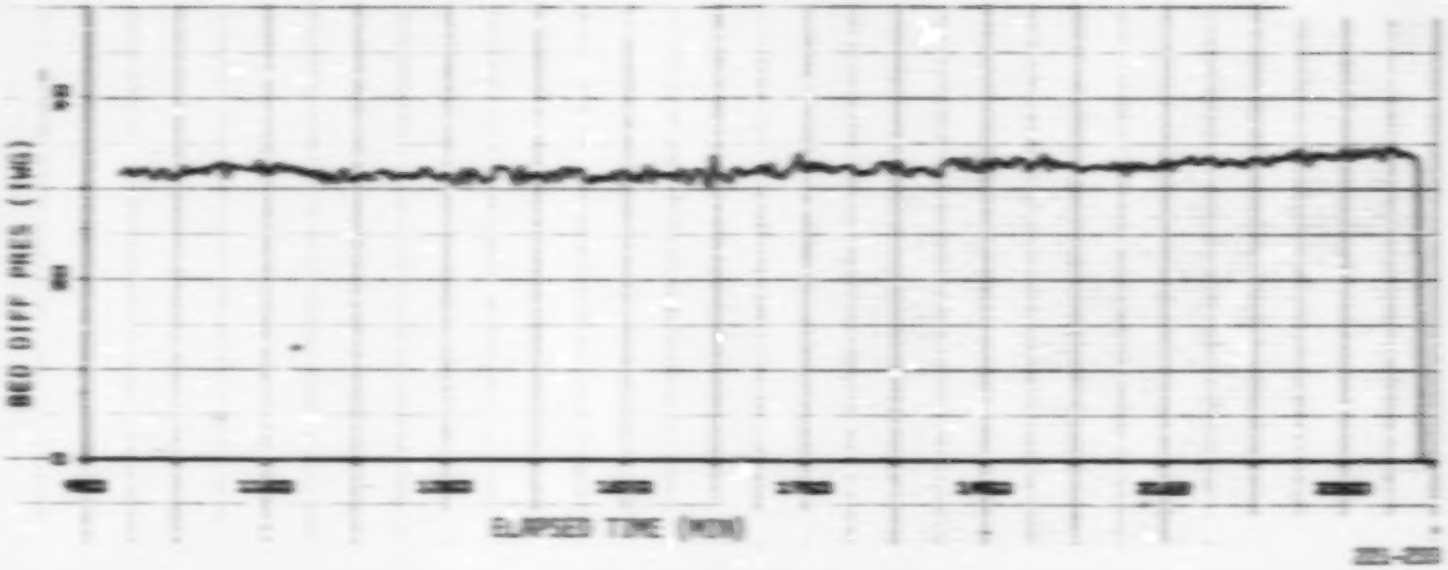


Figure 5-13 LP-8 Fluid Bed Pressure Drop

Exhaust Gas Sampling-

The gas analysis equipment described in Section IV and Appendix C was used to monitor the exhaust gas constituents. The results are summarized in Table 5-9. The CO_2 readings averaged 6.8 percent and are very consistent. The CO readings averaged 41.7 ppm with a tendency to increase at the end of the 24-hour period, probably due to operation on one feed line. The CH_x readings averaged 14.4 ppm and are quite consistent. The NO_x readings averaged 162.2 ppm and are consistent. The SO_2 readings were lower than originally expected and fell into the instrument resolution range of 20 ppm. The O_2 readings averaged 11.7 percent and are very consistent. The HCl readings averaged 90.3 ppm and show considerable fluctuation which is probably due to their being based on discrete samples rather than averages as in the case for the other constituents.

A summery of the particle samples taken during the 24-hour period is presented in Table 5-10. These samples were taken at the inertial separator outlet by isokinetic sampling and the particle counts were then made with a Coulter counter. Two samples were taken at each 3-hour interval. A total loading was performed on the first samples and counts for greater than 2 and 5 microns respectively, performed on the second sample.

It is apparent from this data that plugging of the inertial separator probably occurred between the first and third sampling interval. This can be seen in the sharp increase in total loading that occurred between the third and ninth hour samples. Inertial plugging was verified in the post-test inspections which revealed that ash in the hopper had reached

Table 5-9. LP-8 GAS SAMPLING VOLUMETRIC BASIS

Period[a]	CO_2 (%)	CO (ppm)	CH_x (ppm)	NO_x (ppm)	SO_x (ppm)	O_2 (%)	HCl (ppm)
1	6.8	27.0	6.8	162.2	< 20	11.8	40.5
2	6.5	27.0	10.1	168.9	< 20	11.6	92.9
3	6.8	27.0	11.5	162.2	< 20	11.5	43.6
4	6.8	40.5	16.9	168.9	< 20	11.5	110.6
5	6.8	40.5	14.9	168.9	< 20	11.8	111.0
6	6.8	54.1	13.5	162.2	< 20	11.8	97.7
7	6.8	40.5	16.9	155.4	< 20	11.6	102.8
8	6.8	40.5	14.9	155.4	< 20	11.7	122.4
9	6.8	27.0	16.9	162.2	< 20	11.9	63.0
10	6.8	40.5	16.9	162.2	< 20	11.8	84.4
11	6.8	54.1	14.9	155.4	< 20	11.6	119.7
12	7.2	81.1	16.9	162.2	< 20	11.5	95.1
Av.	6.8	41.7	14.4	162.2	< 20	11.7	90.3

[a] Periods denote 120 min intervals.

Table 5-10. LP-8 PARTICLE SAMPLING

Control time (hr)	Sample 1	Sample 2	
	Total loading (grain/scf)	Loading > 5μ (grain/scf)	Loading > 2μ (grain/scf)
3	0.0566	0.02541	0.06727
6	0.1438	0.04996	0.12985
9	0.3472	0.08331	0.16708
12	0.2305	0.17819	0.27140
15	0.3975	0.06970	0.13624
18	0.3083	0.11558	0.21918
21	0.1784	0.14696	0.22591
24	0.6145	0.20323	0.35940

the tube bottoms. Vibrators were installed to keep the hopper clear during future tests.

Superficial Velocity-

Superficial velocity is presented in Figure 5-14. This data shows superficial velocity was in the 5.8 to 6.0 fps range during two feedpipe operations, and dropped to the 4.9 to 5.0 fps range on one feedpipe operation. The drop in velocity is due to the reduced combustor air flow caused by shutting down one feed line and venting the same amount to maintain fluidizing air flow. Superficial velocity is well within the 4 to 8 fps range required by the test plan.

Post Test Inspection

After cooldown, the vessels were inspected to establish the system condition. The combustor was in excellent condition. The bed depth measured 25 inches which verified the bed pressure drop measurements made during the test. Approximately 10 pounds of alumina clinker material formed on the exhaust pipe extending into the combustor. Five pounds of deposit formed on the outside surface of the combustor exhaust duct separated from the duct and were found on top of the bed below the exhaust duct.

The sand and ash collected in the first stage separator was within approximately 1.5 feet of the exhaust pipe. The weight of material collected was 8769 pounds. This material had fused into one large clinker and had to be broken apart for removal. Only a thin area on the sides, top, and bottom remained loose. A large clinker (23.5 pounds) formed

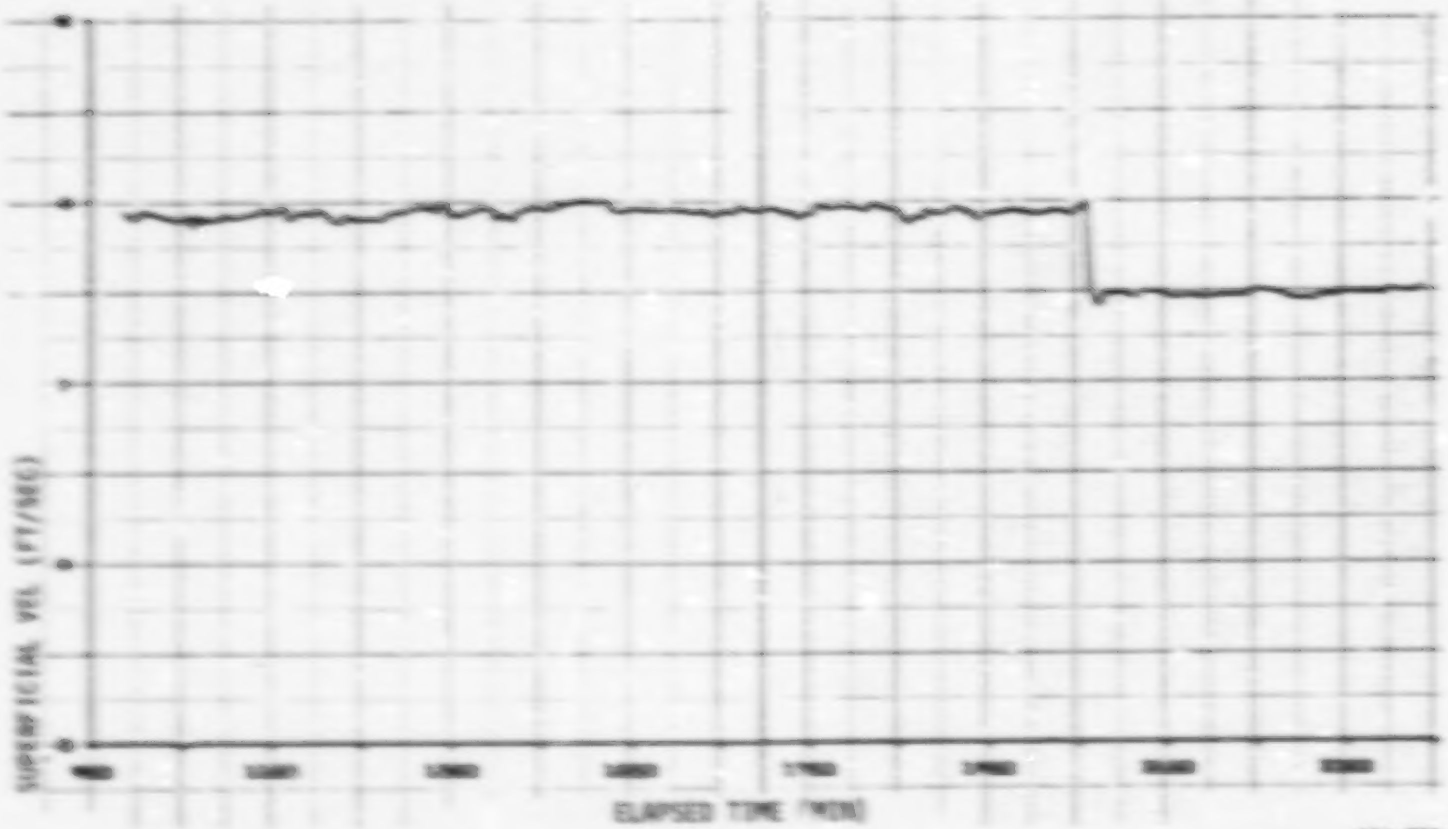


Figure 5-34 LP-8 Superficial Velocity

on the impingement baffle. Other large clinkers (108.5 pounds) formed on the wall and top surface area where the exhaust was deflected by the baffle.

In the inertial separator hopper, ash had built up until it reached the tube ash-outlets. Approximately 25 percent of the ash generated remained in the hopper.

The baghouse hopper and filter bags were clean except for a slight ash deposit.

During the test series, one case of splitter chute plugging and one case of feed line plugging were experienced. A total quantity of 171,260 pounds of residential solid waste was received and processed. Shred rate averaged between 1.4 and 2.0 tons per hour; however, the efficiency of the air classifier was erratic due to its sensitivity to variations in solid waste moisture content and composition. Average of light fraction separated ran between 75 and 85 percent of the received solid waste.

Conclusions

The following conclusions were drawn from the results of the LF-6 testing series:

1. In general the solid waste handling system performed adequately during the testing series. The shredding and air classification operations on municipal solid waste produced a fuel form having very satisfactory physical properties for energy recovery through combustion in a fluidized bed reactor. However, the marginal operation of the air classifier indicated that design efforts should be

initiated to produce an air classifier less sensitive to variations in solid waste moisture content and composition.

2. Test results indicated that the vertical fluidized combustor was a highly efficient, easily fed, readily controlled reactor capable of utilizing low quality fuels.
3. Results of low pressure operation of the solid waste fired, fluid bed combustor showed an average combustion efficiency of 99.7 percent.
4. No problem with fluidized bed residue buildup was experienced during the testing series. Relatively large metal and inert particles entering the active bed experience gradual oxidation or attrition to typical bed size particles and are eventually elutriated and collected by the particle separators. No bed material agglomeration was experienced in the 1270° to 1450° F bed temperature range.
5. Gas phase combustion above the fluidized bed has been reduced to acceptable values without resorting to undesirable remedies such as extensive internal bed structures, numerous fuel feed points, deeper bed, multi-stage combustors, etc.
6. Earlier combustor freeboard and exhaust system deposit problems due to the aluminum content of solid waste appear to have been solved.
7. The use of a residue removal system for the solid waste fired vertical fluid bed combustor during low pressure operation would not be required.
8. The addition of the alumina separator between the fluid bed combustor and first stage inertial separator greatly reduced the high solids input to the first stage inertial separator.

9. The material accumulating in the bottom of the alumina separator must be continually removed or it will fuse into a large clinker.
10. Performance of the inertial separator during the testing series indicated that, although the modifications made to the separator did achieve longer trouble-free operation, the collecting hopper unloading and individual cyclone tube ash outlet plugging problem still existed.
11. No evidence of serious hot gas system material corrosion or erosion problems has been found.

TASK LP-11 TESTING (20-SERIES TESTS)

Test Summary

Continuous operation of a fluid bed combustor burning solid waste in excess of the required 48 hours under automatically controlled conditions was successfully accomplished with the completion of this test. The second stage inertial separator outlet temperature was controlled by a process control system to within 10° F of the desired set-point temperature for over 40 hours, with an additional 9 hours within 30° F. An on-line gas analyzer sampled exhaust gases continuously, while discrete samples were taken every 2 hours for HCl, and every 3 hours for particle count determination. A pre-test failure in the SO_2 system resulted in no recording of SO_2 data, but successful operation of the remainder of the on-line system resulted in a continuous record of O_2, CO, CO_2, NO_x, and CH_x. Sand and ash were successfully transported from both inertial separators and the sand separator. Combustion efficiency computed by the two methods indicated an efficiency of 99.7 percent. The superficial velocity was maintained within 4.0 to 5.4 feet per second throughout the test with a nominal value between 5.2 and 5.3 feet per second.

Test Objectives

The primary purpose of this test was to verify the adequacy of the computerized control system to automatically control the solid waste fueled bed combustor and its ancillary equipment. Specific test objectives are cited below:

1. Test duration: 48 hours continuous operation
2. Maximum variance temperature from setpoint: ± 10° F for 36 hours and ± 30° F for 12 hours,or ± 10° F for 48 hours.
3. Temperature step changes:
    a. from 1400° F to 1430° F and back
    b. from 1400° F to 1370° F and back
4. Fuel: solid waste only
5. Combustion efficiency: 95 percent (two methods)
6. Continuous residue removal
7. Energy and material accounting: within 5 percent
8. Fluid bed height: ± 2½ inches
9. Elutriation: less than 4 percent per hour of sand not passing a 30 mesh screen
10. Particulate: determine particulate loading of exhaust gas
11. Gas: determine percentage of the following chemical compounds: SO_2, NO_x, HCl, CO, CO_2, and CH_x
12. Superficial velocity: between 4 and 8 feet per second

13. Clinkers: none larger than can be removed by the residue removal system

Test Setup and Hardware Description

The LP-11 test setup is shown schematically in Figure 5-15. Included in this test configuration were the vertical combustor and particle separators used during the LP-8 test series, an additional inertial separator, and the modified solid waste handling system.

Hot Gas System-

The vertical combustor system used during the LP-11 test series was essentially identical to the combustor system used in the LP-8 test configuration. The gas from the fluid bed was passed through the three stages of particle separators, and was then exhausted to the atmosphere downstream of the temperature sensing point on the third stage separator after having been passed through the water spray. Residue from the second and third stage separators was pneumatically transported to the baghouse filter.

In addition to the newly added inertial separator, other changes and additions that were made to the hot gas system since the completion of the LP-8 test series were: (1) the addition of pneumatic vibrators on the hopper cones of both inertial separators, (2) the enlargement of the ash outlet on the second stage separator hopper to 6 inches, (3) the addition of a spinner duct to the alumina separator, (4) the addition of a sand removal system to the alumina separator, and (5) the addition of the necessary piping and control hardware required to pneumatically

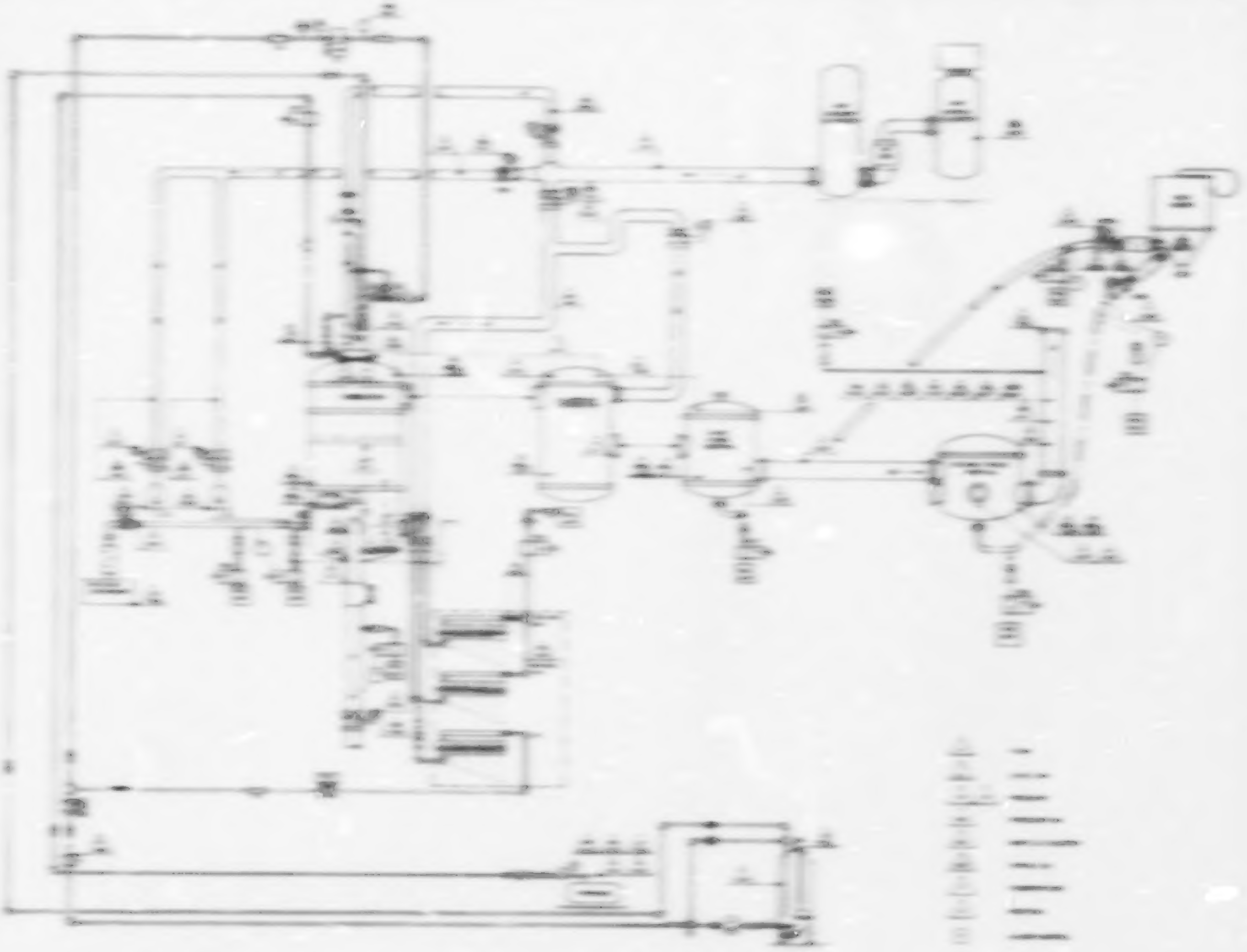


Figure 5-35 LP-11 Test Setup

transport the residue from the newly added third stage separator to the baghouse filter.

The combustor and particle separator configuration is shown in Figure 5-16. Details of the hot gas system have been described previously in Section III.

Control System-

The temperature of the cleaned gas leaving the second stage inertial separator (third stage separator) was the primary parameter to be controlled. The basic control concept used for this test was the controlling of the fluid bed and hot gas system outlet temperatures by modulating the fuel flow into the combustor. Automatic control of the pilot plant was implemented by coupling a process control computer through eight, two and three-mode process controllers. Software was written and utilized to maintain setpoint control of various key parameters, to control or monitor numerous on/off and status functions, and to log test data for post-test processing. A simplified block diagram of the control system is presented in Figure 5-17. Only the primary active elements of the test are included. Start up, secondary, and inactive sections of the system have been omitted for clarity. Refer to Section IV for a summary of the LP-II control system and software structure. Temperature sensors, and pressure sensors and switches that were used to control, monitor and analyze pilot plant operation during the 48-hour test period are shown in Figure 5-15, and are identified in Tables 5-11 and 5-12. Fisher controller settings are identified in Table 5-13.

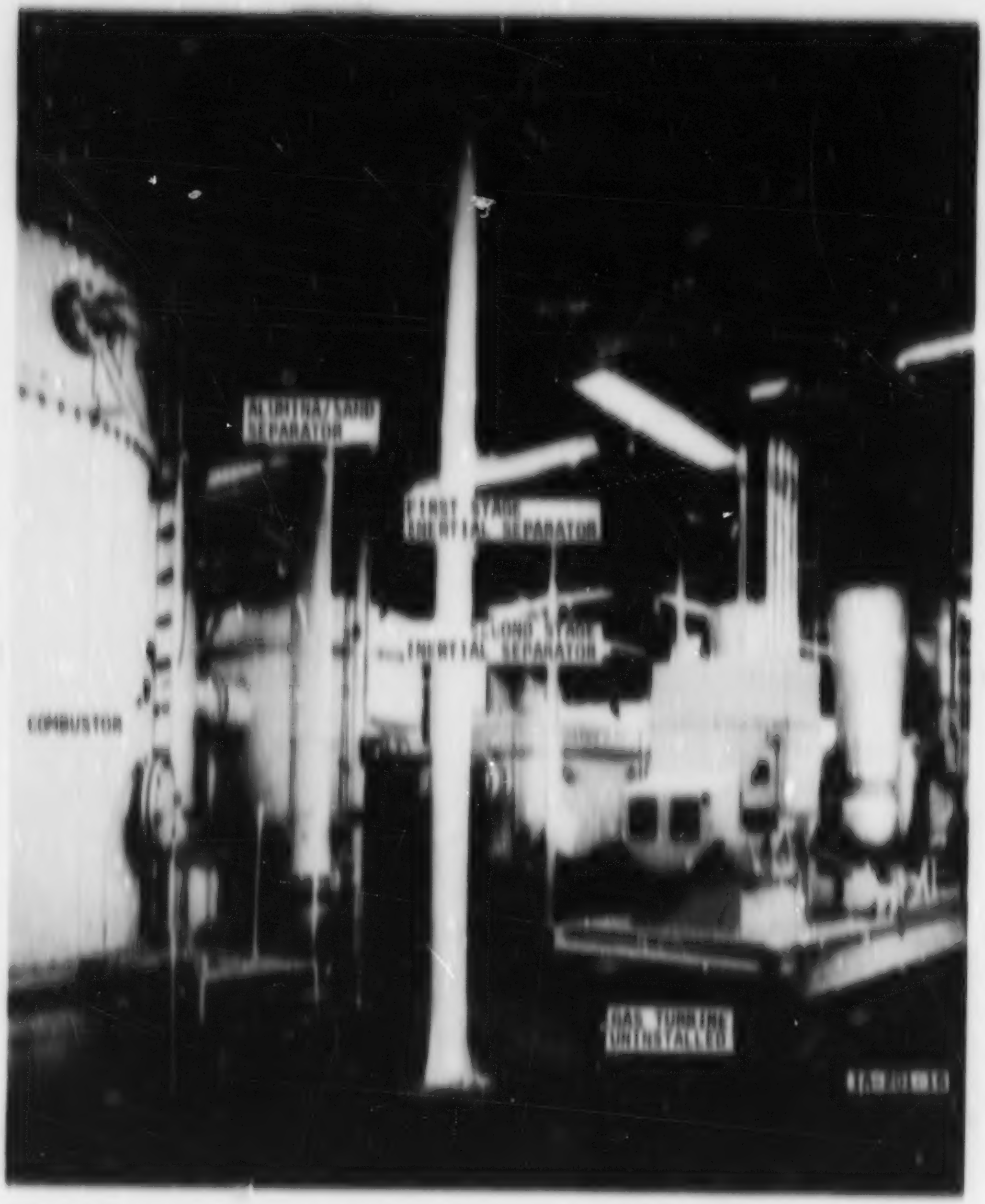

ALUMINA/SAND SEPARATOR
FIRST STAGE INERTIAL SEPARATOR
SECOND STAGE INERTIAL SEPARATOR
COMBUSTOR
GAS TURBINE UNINSTALLED

Figure 5-16 LP-11 Combustor and Particle Separator Configuration

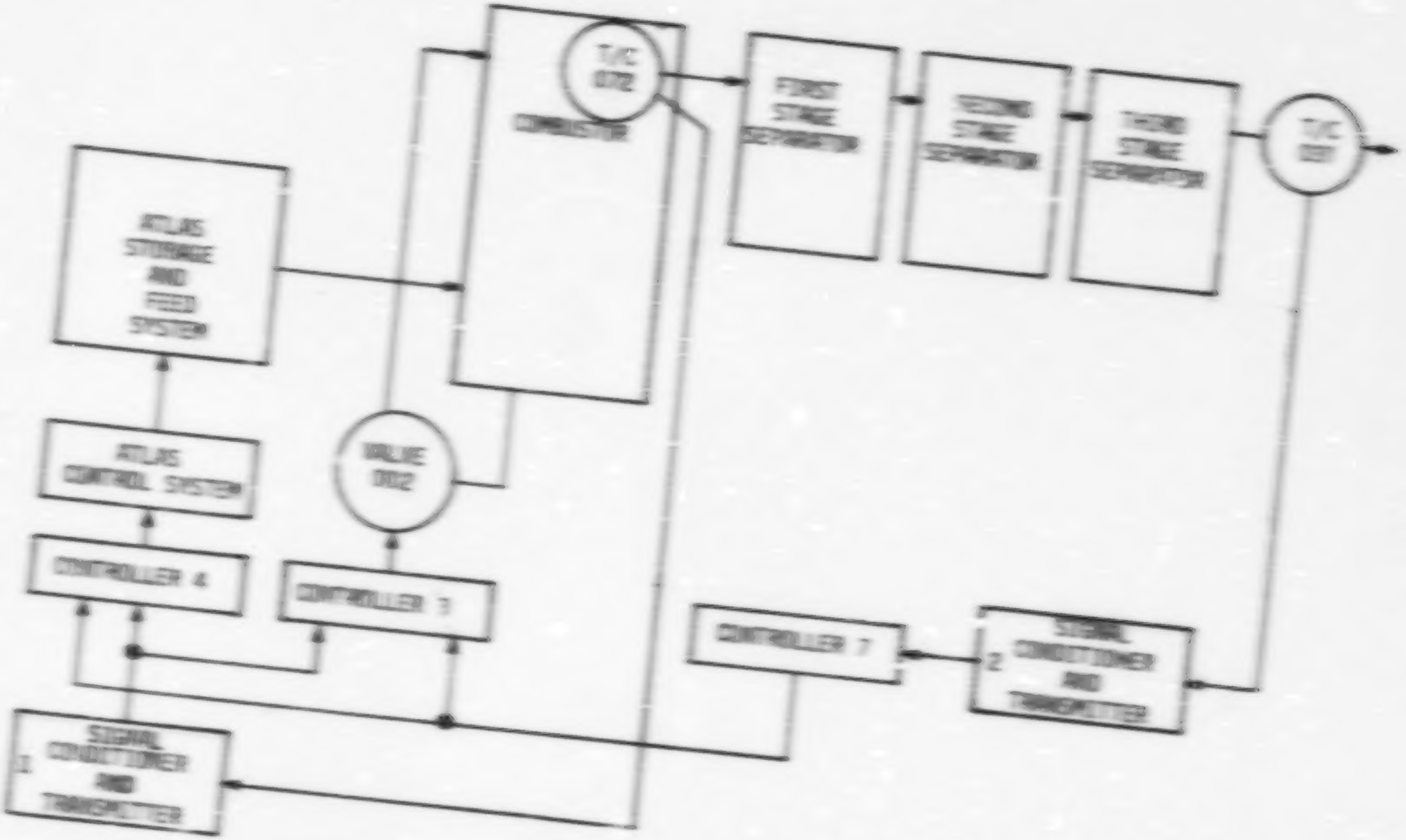

ATLAS STORAGE AND FEED SYSTEM
ATLAS CONTROL SYSTEM
CONTROLLER 4
VALUE 002
CONTROLLER 1
T/C 072
COMBUSTOR
FIRST STAGE SEPARATOR
SECOND STAGE SEPARATOR
THIRD STAGE SEPARATOR
T/C 037
CONTROLLER 7
2
SIGNAL CONDITIONER AND TRANSMITTER
1
SIGNAL CONDITIONER AND TRANSMITTER

Figure 5-17 LP-11 Simplified Control Loop Block Diagram

TABLE 5-11 LP-11 TEMPERATURE SENSORS

Thermocouple I. D.	Measurement[a]
000	Fluid Bed 9"
001	Fluid Bed 9"
002	Fluid Bed 9"
003	Fluid Bed 9"
004	Fluid Bed 9"
005	Fluid Bed 9"
006	Combustor Plenum 9"
007	Combustor Plenum 9"
008	Distributor Plate Surface
009	Distributor Plate Surface
010	Fluid Bed 0"
013	Combustor wall
014	Freeboard 10"
015	Freeboard 10"
016	Combustor wall just below feedline - surface
017	Combustor dome - surface
018	Diesel oil supply - 1"
019	Aluminum vessel wall - surface top dome
020	1st Stage Inertial Separator top dome - surface
021	1st Stage Inertial Separator wall - side surface
024	1st Stage Inertial Separator material removal line between water injection point and valve 009 - surface
025	1st Stage Inertial Separator outlet gas - 1"
026	1st Stage Inertial Separator outlet pipe-surface
027	2nd Stage Inertial Separator internal gas - 10"
028	2nd Stage Inertial Separator top dome - surface
029	2nd Stage Inertial Separator side wall - surface
031[b]	2nd Stage Inertial Separator outlet - 1" (Well upstream of water injection point)
032	2nd Stage Inertial Separator material removal line between water injection point and valve 0/0 surface
035	Propane supply - 1"
036	Low Pressure compressor outlet gas - 1"
072	Aluminum vessel inlet gas - 1"

---

[a] Dimensions associated with each T/C indicate length that the T/C projects into the associated area. When "surface" is noted, the T/C is tack welded to the noted surface.

[b] Control Thermocouple

TABLE 5-12 LP-11 PRESSURE SENSORS AND SWITCHES

Item Identification	Measurement
Pressure Transducers	
101	Plenum Pressure
107	Compressor Outlet
120	Bed ΔP
121	Distributor Plate ΔP
123	1st Stage Inertial Separator ΔP
124	2nd Stage Inertial Separator ΔP
125	Aluminum Vessel ΔP
140	Feedline No. 1 Flow pitot tube
141	Feedline No. 2 Flow pitot tube
146	Combustor inlet pitot tube
160	Diesel flow to solid waste combustor
Position Transducers	
200	Outfeed conveyor level
220	Feed air line 1 valve position
221	Feed air line 2 valve position
222	Low Pressure air flow control valve
223	Large overboard dump valve position
225	Inlet No. 1 to baghouse valve position
226	Inlet No. 2 to baghouse valve position
231	Bypass valve position
232	Diesel fuel valve position
241	Sweep speed (command)
242	Atlas outfeed speed (command)
Miscellaneous	
400	Accumulated weight over conveyor
402	Oxygen analyzer output
403	Carbon monoxide analyzer output
404	Carbon dioxide analyzer output
405	Hydrocarbon analyzer output
406	Hydrochloric analyzer output
407	Sulphur dioxide analyzer output
408	NO and NO_2 analyzer

TABLE 5-12. (continued) PRESSURE SENSORS AND SWITCHES

Temperature I.D. Switches	Measurement
500	Classifier temperature
502	Atlas hydraulic supply
Pressure and Flow Switches	
600	Atlas internal pressure
601	Backheat fuel pressure
604	Baghouse internal pressure
615	Shop air pressure
620	Low Pressure Compressor Filter ΔP
660	Backheat burner cooling air flow
661	Oil gun mix flow (Air)
662	Oil gun cooling flow (Air)
Position Switches	
706	Diesel oil supply level
721	Low Pressure valve #729 position
724	Low Pressure comp. outlet valve #007 position
730	Belt position - transfer conveyor
731	Belt position - weigh conveyor
733	Exhaust cap status
736	Valve 005 status
760	Shredder vibration switch
Miscellaneous	
900	Shredder conveyor status
901	Classifier status
903	Atlas sweep status
904	Atlas outfeed conveyor status
905	Transfer conveyor status
906	Weigh conveyor status
907	Feeder valve No. 1 status
908	Feeder valve No. 2 status
909	Ignitor transformer status
910	Baghouse dump valve status
961	Flame sensor switch

Table 5-13. LF-11 TEST, FISHER CONTROLLER SETTING

Controlled parameter	Fisher Controller					
	No. 1	No. 3	No. 4	No. 5	No. 6	No. 7
PB %	100	50	30	40	40	100
Reset	10	2.0	2.0	10	10	0.1
Range	all	all	all	all	all	all
Control action	Direct	Reverse	Reverse	Direct	Direct	Reverse
Rate	~0	2.0	1.0	-	-	-
Control mode	Manual	Remote	Remote	Remote	Remote	Remote
Controlled element	Valve 005	Valve 002	Atlas Control System	Valve 003	Valve 001	Fisher #3 or #4[a]
Controlled variable	Combustor air flow	Oil flow	Solid waste feed	#1 Feedline air flow	#2 Feedline air flow	Fisher setpoint

[a] Cascaded with controller #3 for fuel oil feed control or with controller #4 for solid waste feed control

Solid Waste Handling System

Results of the LP-8 test series and longer duration tests scheduled for the LP-11 series established requirements for improved through-put and reliability in the solid waste handling system. (Figure 5-18.) Changes were made to both the shredder/air classifier/pneumatic transfer subsystem and the Atlas store/combustor feed subsystem (Figure 5-19). Details are discussed in Appendix A and are briefly summarized below:

1. The direct-coupled metal air classifier used in previous tests was replaced by an experimental wooden air classifier.
2. A shredder outfeed conveyor equipped with two paddle type load levelers to maintain a constant 3-inch level of waste feed at the inlet of the new air classifier was added between the shredder and air classifier.
3. A reject fraction conveyor was added to the air classifier reject material outlet.
4. The two 16-inch airlock feeder valves were replaced by two 30-inch Esco Rotafeeders (Figure 5-20). Each valve had volumetric capacity of 30 cubic feet per minute.
5. The two 5-inch diameter combustor feed pipes were replaced by two 6-inch diameter feed pipes.

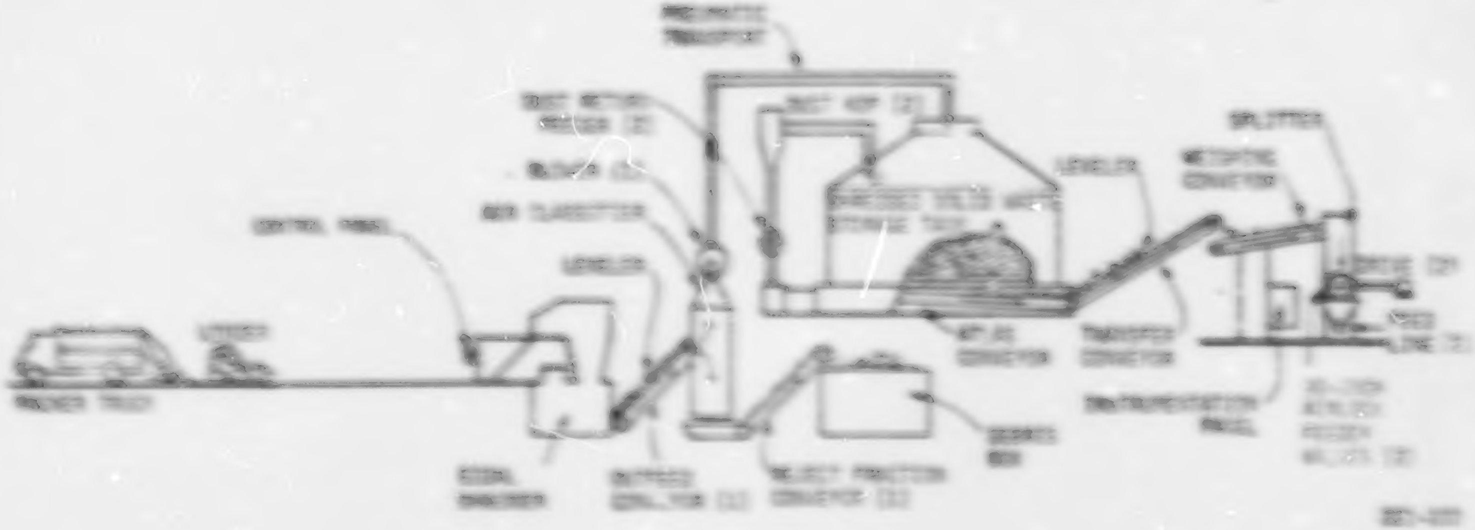

PNEUMATIC TRANSPORT
DUST RETURN SYSTEM (2)
BLOWER (2)
AIR CLASSIFIER
CONTROL PANEL
LEVELER
LOADER
PACKER TRUCK
OUTFEED CONVEYOR (2)
REJECT FRACTION CONVEYOR (2)
DEBRIS BOX
SHREDDED SOLID WASTE STORAGE TANK
CONVEYOR
TRANSFER CONVEYOR
LEVELER
WEIGHING CONVEYOR
SPLITTER
FEED LINE (2)
INSTRUMENTATION PANEL
30-INCH ROTARY FEEDER VALVES (2)

Figure 5-28 LP-II Solid Waste Handling System

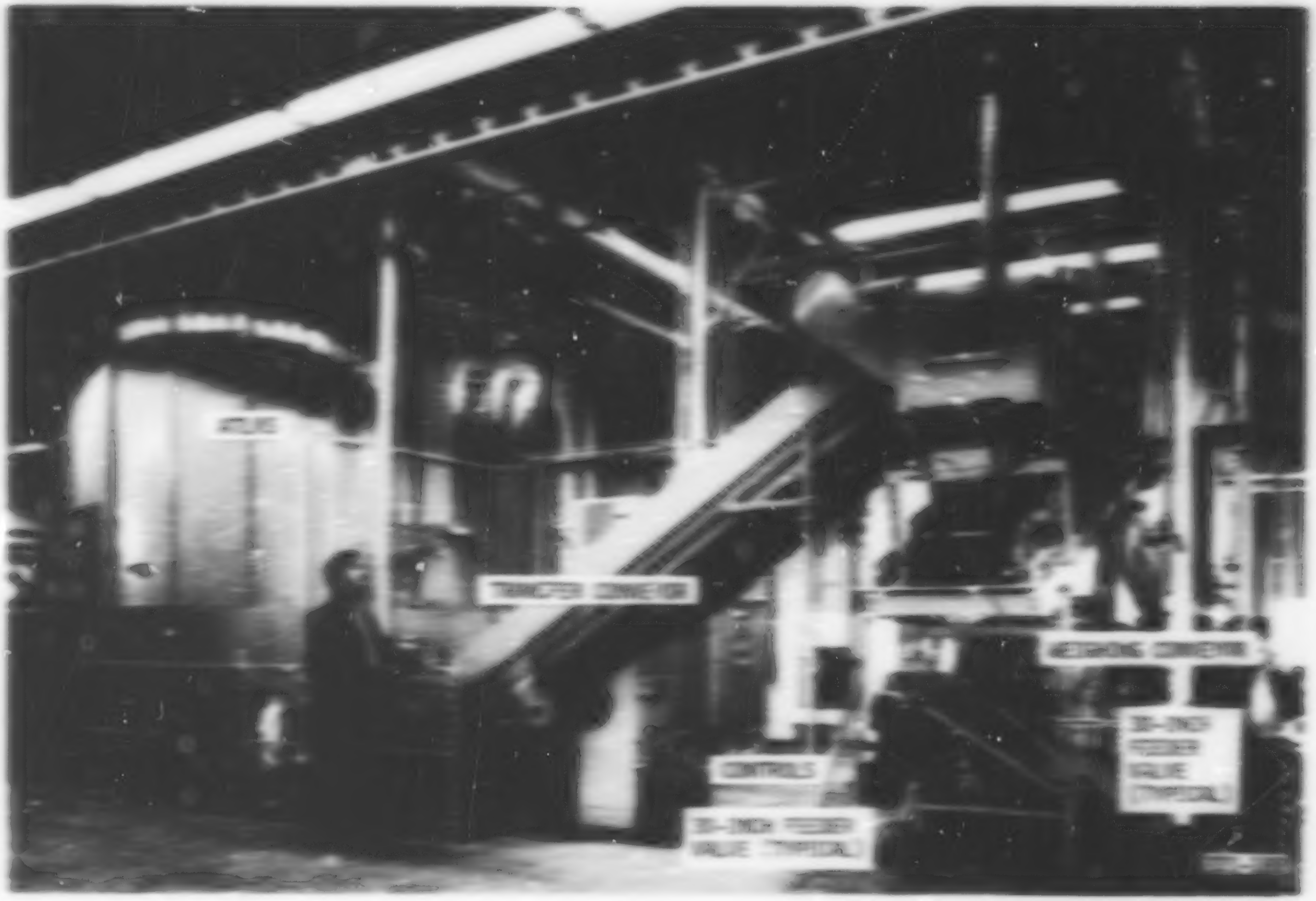

ATLAS
TRANSFER CONVEYOR
WEIGHING CONVEYOR
CONTROLS
30-INCH FEEDER VALVE (TYPICAL)
30-INCH FEEDER VALVE (TYPICAL)

Figure 5-19 LP-11 Atlas Storage and Combustor Feed Subsystem

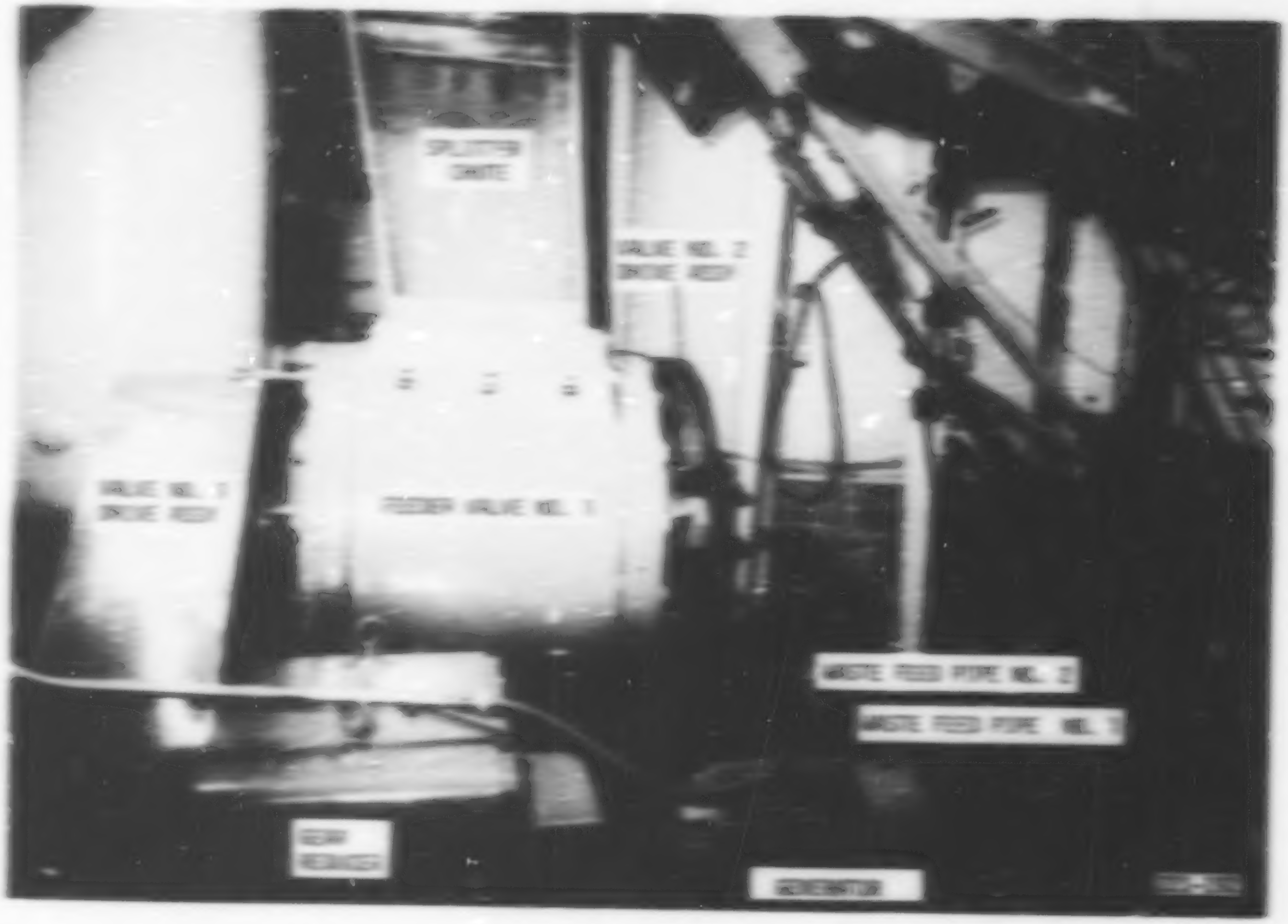

SPLITTER CHUTE
VALVE NO. 2 DRIVE ASSY
VALVE NO. 1 DRIVE ASSY
FEEDER VALVE NO. 1
WASTE FEED PIPE NO. 2
WASTE FEED PIPE NO. 1
GEAR REDUCER
GENERATOR

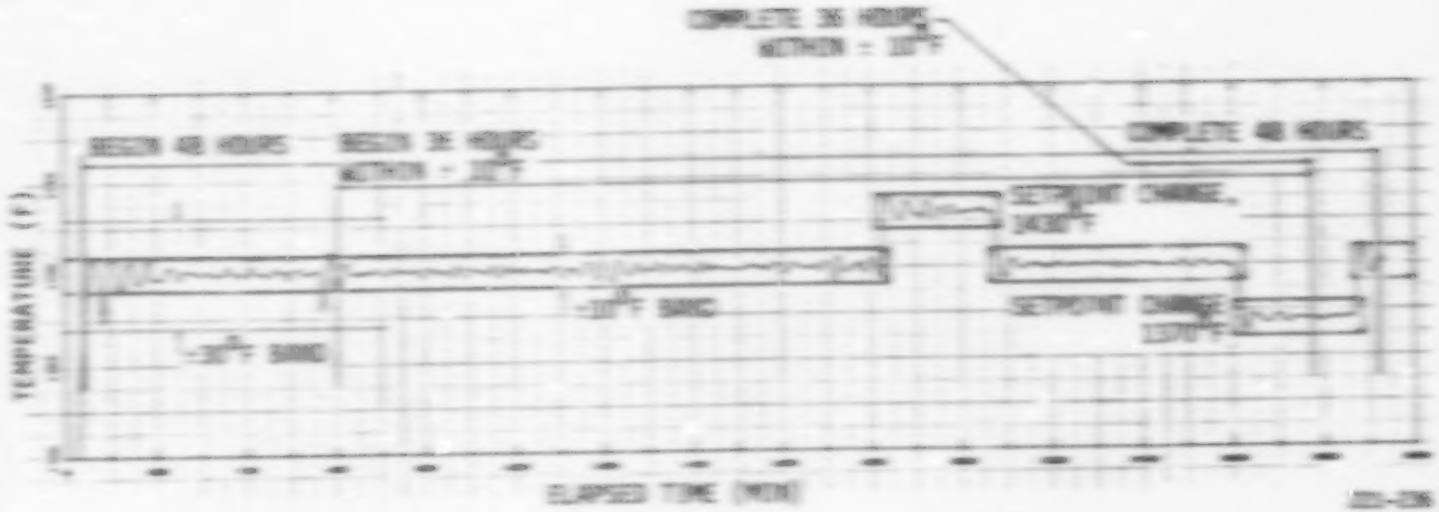
Figure 5-20 30-Inch Feeder Valve Installation

Test Results and Analysis

Exhaust Temperature Control-

The basic test conditions called for controlling temperature at the outlet of the third stage separator to 1400° ± 20° F. Acceptable variations to this schedule were designated by the Project Officer. The alternate condition under which this test was run allowed the control temperature to deviate by ± 30° F from the setpoint but imposed a ± 10° F maximum deviation for a minimum of 36 consecutive hours. Included as part of this schedule was the requirement to increase the nominal setpoint from 1400° F to 1430° F for 4 hours and decrease it to 1370° F for another 4 hours. Deviations from specified limits were allowed during transition. These conditions were satisfied during the course of this test.

Specific key temperatures were sampled and recorded on hard copy at the rate of approximately once per minute. Larger quantities of data were sampled at the rate of roughly every 6½ minutes and stored on the computer disc file for post-test processing. Figure 5-21 presents a plot of the control thermocouple at this slower sampling rate. Elapsed time began when the low pressure compressor was turned on. By ET = 43 minutes, the control temperature was within ± 20° F of 1400° F and continuous operation for 48 hours began. During this 48-hour (2880 minute) period the control temperature exceeded ± 20° F for a total of 8 minutes. At ET = 84 minutes, the temperature error was below -20° F for 4 minutes and again at ET = 575 minutes for 4 minutes. At the latter time the minimum test temperature of 1370° F was reached due to a problem with the solid waste feed system which virtually shut off the fuel flow for a



5-21 LP-11 Third Stage Separator Exhaust Temperature short time. The dynamic oscillations of the control temperature due to this perturbation damped to within ± 10° F by ET = 605 minutes. From this time until test shutdown at ET = 3209 minutes, a total of 40 hours and 25 minutes, the control system maintained ± 10° F except for two allowed deviations during transitions from one setpoint to another. The first of these occurred within the required continuous 36 hours and while stepping up to 1430° F at ET = 1836 minutes. The second was at ET = 2886 minutes during the step back to 1400° F from the 1370° F setpoint. The required 48-hour period was completed at ET = 2923 minutes. Solid waste consumption continued however, for an additional 107 minutes (not shown) before shutdown.

Statistics of the control temperature are shown in Table 5-14. Except for the statistically non-significant six data point period at the end of the 48 hours, the recorded control thermocouple had a mean value within 0.2° F of the desired setpoint. The variance and standard deviation of each setpoint group is also shown. For comparison, the 24-hour LP-8 test utilized process controllers only for the control of the first stage inertial outlet temperature to 1450° F. The mean of that test was 1456° F with a standard deviation of 7.6° F.

These results illustrate some of the advantages of the hybrid control approach; an inner analog controller loop based on measured sand separator top gas temperature and computer-generated setpoint. This inner loop setpoint was re-evaluated every 10 seconds by an outer control loop mechanized in the digital computer. Since both the setpoint and process variable measurement (i.e., the second stage inertial separator

Table 5-14. CONTROL TEMPERATURE STATISTICS

Elapsed time duration (sec)	Number of points	Setpoint (°F)	Mean (°F)	Variance (°F)^2	Standard deviation (°F)
40 - 1820	308	1400	1399.8	12.5	3.5
1840 - 2070	42	1430	1430.2	10.4	3.2
2080 - 2570	93	1400	1399.8	2.1	1.4
2575 - 2875	48	1370	1370.0	4.0	2.0
2880 - 2925	6	1400	1398.3	14.3	3.7

outlet gas temperature) for the integrating type of outer loop control are contained in computer memory, very precise steady state control is obtained.

The corollary is that the comparatively high bandwidth analog control loop "floats" in setpoint as required but avoids needless loading of the computer with high frequency calculations.

Exhaust Gas Sampling.

An on-line gas analyzer was used for the determination of all gas constituents except HCl. Single samples taken at 2-hour intervals were titrated by the Volhard method for HCl level determination. The data obtained from the on-line system, averaged over 24 2-hour intervals, are presented in Table 5-18 along with the discrete HCl data. The SO_2 battery cell leaked and shorted the system, making the SO_2 recording meaningless. The on-line system was zeroed to an atmospheric air background and the hydrocarbon analyzer indicated a slightly negative production from the combustion process. All the data indicated consistent readings except the HCl, which had large fluctuations. This may be due to the composition of the fuel during each period, a result of single point sampling or a result of errors inherent in the technique used for HCl determination.

The exhaust gas was sampled isokinetically using a wet impingement technique. (See Appendix C.) Two successive samples were taken at 3-hour intervals. The first sample was dried and weighed to determine the total particle loading; the second was subjected to analysis using a

Table 5-15. LP-11 EXHAUST GAS COMPOSITION (VOLUMETRIC BASIS)

Period[a]	CO_2 (%)	CO (ppm)	CH_x (ppm)	NO_x (ppm)	SO_2[b] (ppm)	O_2 (%)	HCl (ppm)
1	6.0	30	0	157	NA	13.5	210.0
2	6.0	"	"	140	"	13.2	242.8
3	5.8	"	"	124	"	13.0	173.8
4	6.0	"	"	130	"	12.8	197.1
5	6.0	"	"	124	"	13.5	197.1
6	5.8	"	"	135	"	13.5	164.3
7	5.8	"	"	140	"	13.5	145.5
8	5.8	"	"	140	"	13.5	116.9
9	5.8	"	"	135	"	13.5	84.5
10	6.0	"	"	135	"	13.5	141.5
11	5.8	"	"	140	"	13.5	187.1
12	5.8	"	"	140	"	13.5	141.9
13	5.4	"	"	135	"	13.5	199.8
14	5.4	"	"	150	"	13.8	151.2
15	6.2	"	"	170	"	12.8	198.9
16	6.0	"	"	145	"	13.0	115.2
17	6.0	"	"	140	"	13.0	119.2
18	5.8	"	"	135	"	13.2	160.2
19	5.8	"	"	135	"	13.2	256.9
20	5.8	"	"	135	"	13.5	122.5
21	5.5	"	"	135	"	13.5	140.4
22	5.5	"	"	135	"	14.0	138.9
23	5.5	"	"	135	"	13.8	129.6
24	6.0	"	"	135	"	13.2	137.8
Av.	5.81	30	0	138.5	-	13.4	161.1

[a] Periods are at 120 minute intervals

[b] NA = not available

Coulter counter to obtain a size distribution. Particle sampling results are cited in Table 5-16.

Bed Maintenance and Material Balance-

Pre- and post-test measurements indicated a bed height growth of 2 inches (from 24 to 26 inches) or, based on constant density, an 8.3 percent weight increase. The measured pressure drop across the fluid bed is shown in Figure 5-22; the rise in pressure drop is a result of the bed weight increase.

A tabulation of the inerts actually weighed, computed, or estimated appears in Table 5-17. The clinker and the sand or ash which accumulated in each vessel or hopper was weighed after the test. Bed growth was computed based on the height change mentioned earlier and the ash exiting the main exhaust was computed using average particle loading. The weight of ash leaving the sand bin vent and the baghouse exhaust was estimated by comparing the appearance of each exhaust density with the known main exhaust density. Compared to the total solid waste fed, the total inerts from Table 5-17 (including flyash) corresponds to a 14.79 percent inert fraction.

Small solid waste samples were taken from the outfeed conveyor at 2-hour intervals during the test. Moisture, inert fractions, and heating value were determined from these samples. The average of all 24 samples yielded an inert fraction of 10.53 percent. The 4.26 percent difference between this value and that based on actual inerts is probably due to the laboratory method of sampling and processing the solid waste. The heavy

Table 5-16. LP-11 PARTICLE SAMPLING

Control time (hr)	Sample 1	Sample 2	
	Total loading (grain/scf)	Loading >5 (grain/scf)	Loading >2 (grain/scf)
3	0.0814	0.0039	0.0135
6	0.1464	0.0272	0.0680
9	0.2313	0.0731	0.1234
12	0.3706	0.0423	0.0899
15	0.3003	0.1224	0.2140
18	0.6146	0.1713	0.3132
21	0.7100	0.1018	0.2664
24	0.5004	0.0997	0.1937
27	0.3892	0.0857	0.1063
30	0.5133	0.1679	0.3234
33	0.5147	0.0830	0.2348
36	0.5105	0.0844	0.2040
39	0.5580	0.1080	0.2753
42	0.3882	0.0719	0.1826
45	0.5716	0.0918	0.2100
48	0.4001	0.0508	0.1505

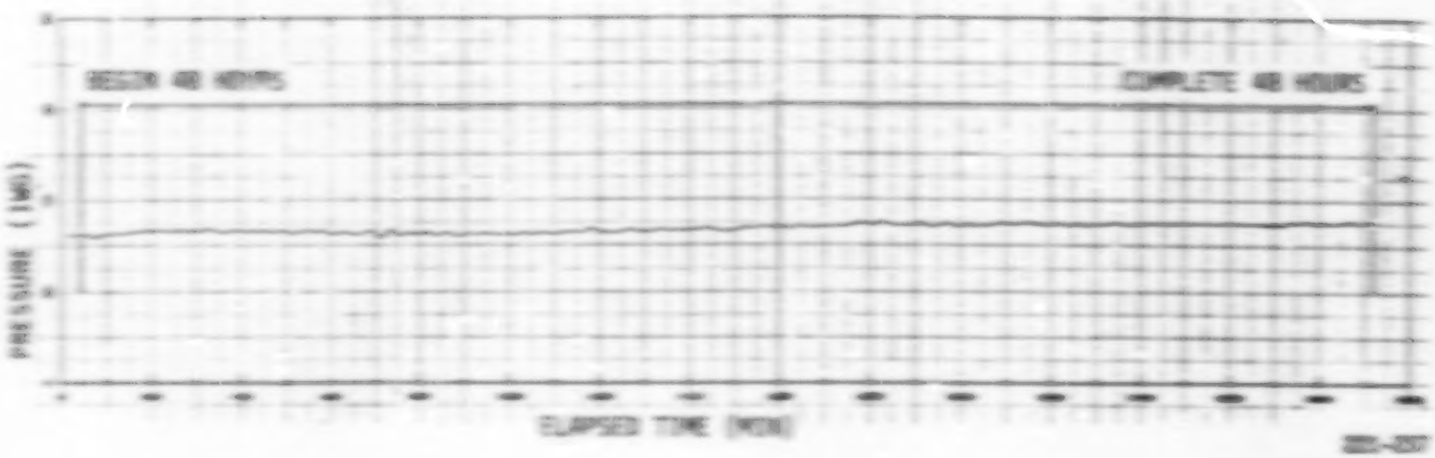


Figure 5-22 LP-11 Fluid Bed Pressure Drop

Table 5-17. LP-11 INERTS ACCOUNTING

Location	Amount (lb)	Amount (%)
Bed growth	550	3.0
Clinker in sand separator	31	0.2
Sand/ash in bottom of 1st stage separator	1,146	6.2
Sand/ash in sand bin	10,200	55.5
Ash out of sand bin vent	22	0.1
Ash in 2nd stage inertial separator	253	1.4
Ash in 3rd stage inertial separator	53	0.3
Ash in baghouse hopper	4,925	26.8
Ash out of baghouse exhaust	650	3.5
Ash out of main exhaust	550	3.0
TOTAL	18,379	100.0

fraction is likely to settle to the bottom both on the conveyor prior to sampling and in the sample storage bag. Thus, since the complete sample is not processed, a few large particles may escape causing distortions in the final result.

Combustion Efficiency Technique- The last column of Table 5-10 contains the efficiency results for this test, using the heat balance technique. Mean efficiency for the 48-hour period was 51.68 percent, but a one-standard deviation for the data of 7.91 percent was computed. The table also shows the principal time varying data which went into the computations.

As shown in the table, a 4.26 percent difference existed between inert fractions derived from the mass balance and the average of laboratory determinations.

In order to correct the measured ash/inert level to that of the inerts accounting, the measured inerts/ash level was multiplied by the ratio of 14.80/10.53 which results in a 24 sample average that is equal to the inerts accounting value. The inert fraction, column C, reflects this correction.

Carbon Combustion Technique- In the carbon combustion method for computing the combustion efficiency it is assumed that unburned carbon in the flue gas exists in the forms of CO (carbon monoxide), HC (hydrocarbons), and C (elemental carbon) only. Therefore,

Table 5-78. LP-11 COMBUSTION EFFICIENCY, HEAT BALANCE TECHNIQUE

	A	B	C	D	E	F	G	H	I	J	K
[illegible]	[illegible]	Moisture fraction	[illegible]	[illegible]	Fuel temperature range (°F)	[illegible]	Heat loss rate (Btu/min)	[illegible]	[illegible]	[illegible]	Combustion efficiency [illegible]
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 5-78 (continued). LP-II COMBUSTION EFFICIENCY, HEAT BALANCE TECHNIQUE

	A	B	C	D	E	F	G	H	I	J	K
Test interval	Av. solid waste flow rate (lb/min)	Moisture fraction	Inert fraction (incl. ash)	Av. air flow rate (lb/min)	Bed temperature range (°F)	Av. 2nd stage outlet temp (°F)	Heat loss rate (Btu/min)	Computed heating value, Q_C (Btu/lb coal)	Heating value from calorimeter, Q_B (Btu/lb)	Lower heating value, Q_L (Btu/lb coal)	Combustion Efficiency $100\ Q_C/Q_L$ (%)
16	43.95	0.3721	0.1457	328.5	1304.9-1299.2	1329.1	7116.7	8128.4	6952.7	7946.8	102.4
17	44.72	0.4370	0.1288	328.3	1298.2-1281.5	1428.1	6674.0	7651.7	7159.4	7868.9	97.28
18	40.57	0.3246	0.1785	328.3	1292.5-1222.8	1295.1	6732.8	7222.5	7512.3	8390.3	85.88
19	42.96	0.3183	0.2059	326.6	1311.9-1225.3	1482.1	6511.6	7781.3	6494.7	7948.2	97.65
20	42.34	0.3932	0.1337	326.1	1325.0-1225.6	1356.8	6756.3	7784.8	7514.6	7688.9	101.3
21	41.36	0.3948	0.1368	329.1	1276.6-1184.3	1308.4	6520.4	7784.4	7303.3	8238.1	96.13
22	41.25	0.3623	0.1276	335.5	1336.3-1274.4	1281.1	5361.2	7789.7	6868.2	7988.2	97.51
23	42.27	0.4200	0.1498	328.6	1274.4-1250.6	1348.7	5586.9	8112.2	6771.5	8048.1	101.2
24	41.98	0.4254	0.1510	328.7	1288.3-1255.6	1382.4	6865.0	8240.6	7294.7	8085.6	100.8
								7912.8[a]		7942.6[a]	99.60[a]
								193.45[b]		195.29[b]	7.988[b]

[a] Mean

[b] Standard deviation

combustion efficiency may be calculated by the following equation:

$$\eta = \frac{\frac{12}{44} a \, (\Delta H_{CO_2}) + \frac{12}{28} b \, (\Delta H_{CO}) + \frac{24}{30} c \, (\Delta H_{HC})}{(\frac{12}{44} a + \frac{12}{28} b + \frac{24}{30} c + d) \, \Delta H_{CO_2}}$$

where: a = weight concentration of CO_2 in flue gas

b = weight concentration of CO in flue gas

c = weight concentration of HC in flue gas

d = weight ratio of C to flue gas

The further simplification of the above equation is based on the assumption that 1 pound of carbon releases 14,087 Btu when converted to CO_2, 3965 when convurted to CO, and about 2000 Btu when forming ethane, (C_2H_6), the most likely hydrocarbon in the flue gas.

Hence,

$$\eta = \frac{\frac{14087}{44} a + \frac{3956}{28} b + \frac{(2)(2000)}{30} c}{(\frac{a}{44} + \frac{b}{28} + \frac{c}{30} + \frac{d}{12}) \, 14087}$$

$$\text{or } \eta = \frac{a + 0.442b + 0.416c}{a + 1.571b + 2.933c + 3.667d}$$

Errors associated with failings fo these assumptions are expected to be small. Therefore, the 99.7 percent average combustion efficiency computed by this method as seen in Table 5-19 is considered to be an accurate representation of the actual efficiency.

The CO_2, CO, and CH_4 weight fractions presented in columns A, B, and C of Table 5-19 were obtained by averaging the results of the on-line

Table 5-19. LP-11 COMBUSTION EFFICIENCY, CARBON COMBUSTION TECHNIQUE

	A	B	C	D	E
Performance interval	Wt. fraction of CO_2	Wt. fraction of CO	Wt. fraction of CH_4	Wt. ratio of carbon (lbC/lb gas)	Combustion efficiency (%)
1	9.1×10^{-2}	2.9×10^{-5}	0.0	5.4×10^{-5}	99.7
2	9.2×10^{-2}	"	"	5.4×10^{-5}	99.7
3	8.8×10^{-2}	"	"	5.0×10^{-5}	99.8
4	9.1×10^{-2}	"	"	5.6×10^{-5}	99.7
5	9.1×10^{-2}	"	"	5.4×10^{-5}	99.7
6	8.8×10^{-2}	"	"	5.3×10^{-5}	99.7
7	8.8×10^{-2}	"	"	4.0×10^{-5}	99.8
8	8.8×10^{-2}	"	"	4.5×10^{-5}	99.8
9	8.8×10^{-2}	"	"	5.0×10^{-5}	99.8
10	9.1×10^{-2}	"	"	4.9×10^{-5}	99.8
11	8.8×10^{-2}	"	"	4.9×10^{-5}	99.8
12	8.8×10^{-2}	"	"	4.8×10^{-5}	99.8
13	8.2×10^{-2}	"	"	4.7×10^{-5}	99.7
14	8.2×10^{-2}	"	"	5.3×10^{-5}	99.7
15	9.4×10^{-2}	"	"	5.4×10^{-5}	99.8
16	9.1×10^{-2}	"	"	5.4×10^{-5}	99.7
17	9.1×10^{-2}	"	"	5.2×10^{-5}	99.8
18	8.8×10^{-2}	"	"	5.8×10^{-5}	99.7
19	8.8×10^{-2}	"	"	5.4×10^{-5}	99.7
20	8.8×10^{-2}	"	"	5.4×10^{-5}	99.7
21	8.3×10^{-2}	"	"	5.7×10^{-5}	99.7
22	8.3×10^{-2}	"	"	5.5×10^{-5}	99.7
23	8.3×10^{-2}	"	"	5.1×10^{-5}	99.7
24	9.1×10^{-2}	"	"	5.3×10^{-5}	99.8
					99.7[a]
					0.05[b]

[a] Mean

[b] Standard deviation

analyzer over 2-hour intervals. The free carbon concentrations in column D were obtained by outside laboratory analysis on 24 samples taken from the baghouse hopper during the test.

Superficial Velocity-

For this test, the superficial velocity was specified to be between 4 and 8 feet per second. As shown in Figure 5-23, this requirement was met for the duration of the test. With a fixed mass airflow through the hot gas system, the changes of superficial velocity are associated with bed temperature variation and combustor bypass flow. Combustor bypass flow is a controllable function that allows the bypassing of the fluid bed by some of the compressor air flow. The air flow is mixed with the gas coming off the bed. The primary function of the bypass air loop is to provide an internal control loop for bed temperature maintenance.

During short periods of problems with support hardware, (e.g., the solid waste feeder valve adapter) caused the bed temperature to drop to levels below the nominal level of about 1325° F. Each of these drops is reflected in Figure 5-23.

Post Test Inspection

All major system components were in excellent condition at post-test inspection. At this time the combustor and first stage separator had been used for a total of 158 hours of solid waste operation, while the third stage separator had been operated for 101 hours. The second stage separator had been operated for a total of 177 hours, since it was used during some of the horizontal combustor tests. The refractory in the

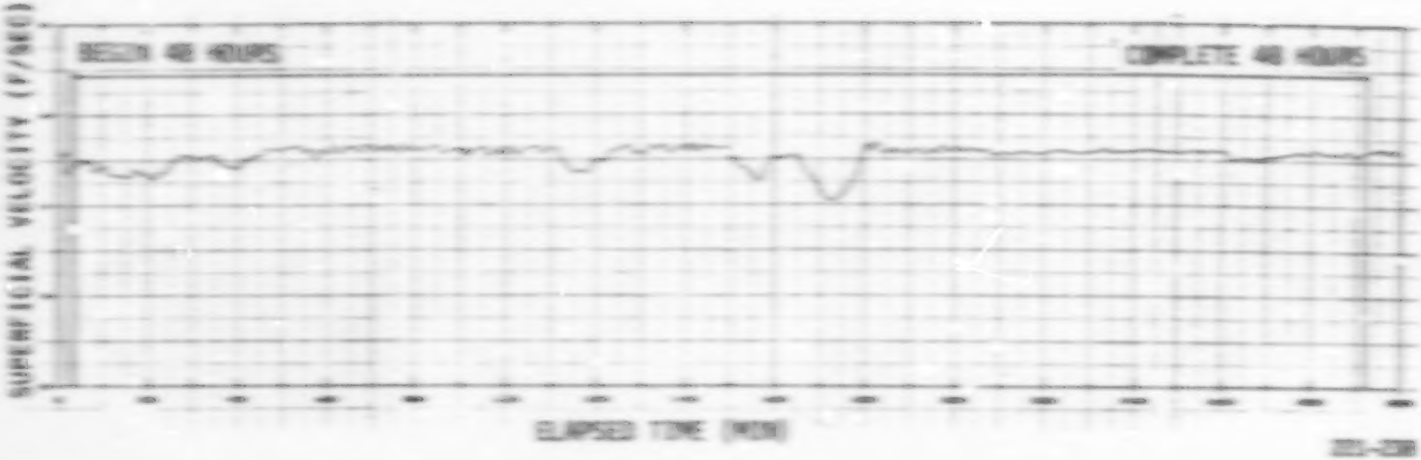


Figure 5-23 LP-11 Superficial Velocity

combustor showed no signs of wear or erosion.

A one cubic foot sample of bed material was examined for metal and found to contain 0.33 pounds. It was therefore expected that 28 pounds (0.33 x 86) of metal would be present in the bed. A total of 316,000 pounds of solid waste have been introduced into the bed since the vertical combustor was commissioned. Allowing for attrition, previously calculated to be 0.004 pounds oxidized per pound present per hour, the required quantity of metal introduced into the bed to provide this result would be 0.0318 percent of the solid waste. The metal content from 5 solid waste samples taken during test run 20-48 averaged 0.032 percent, which is in agreement with the calculated value. During the model test discussed in Section III (Task LP-5), this value was calculated to be 0.17 percent of solid waste. The primary difference is apparently due to the present air classifier which removes most of the metal.

During the test the pressure drop across the distributor plate was observed to increase from 9 to 23 iwg. Post-test inspection revealed a considerable amount of dust buildup on the diffusers. Subsequent bench flow tests of dirty and cleaned diffusers confirmed that the excess pressure drop resulted from the dust. Since previous tests have not experienced this phenomena, the cause has been attributed to the malfunction of the baghouse discussed later in this section. This malfunction allowed large amounts of flyash to escape into the plant. The low pressure compressor intake located 10 feet from the baghouse was continually exposed to dust resulting in high intake air particle loading.

The addition of the spinner duct in the first stage separator resulted in a marked reduction in clinker formation over previous tests. A total of only 31 pounds of clinkers were found in the duct. No erosion of the duct was apparent. The transport of the captured inert material to an off-line storage bin (about 20 feet away) was successfully accomplished. As expected, about 10 percent of the total sand/ash collected by this vessel built up at the bottom until it formed a conical entrance to the discharge point.

The second stage separator had two of the 24 tubes visibly plugged at the ash outlet, but the hopper had only small amounts of ash on the walls. The newly installed vibrators were effectively preventing hopper ash buildup.

The third stage separator hopper was likewise free of major ash deposits. All 80 tubes, however, were plugged or partially plugged at the ash outlet.

The puffback blower of the baghouse assembly was inoperable during approximately 8½ hours of test due to a bearing seizure. This caused an estimated 500 pounds of ash to escape to the atmosphere. Post-test inspection indicated that all other baghouse functions operated properly.

Support of the LP-11 test series required the processing of approximately 290,000 pounds of residential solid waste. Efficiency of the shredder/air classifier/pneumatic transfer subsystem was consistently improved over LP-8 data, with through-put averaging 2 TPH and better and air separation yielding a cleaner cut of light and heavy fraction. The results of experimentation with the wooden air classifier established parameters for design of the full scale 5 TPH air classifier and pneumatic transport system required for the future LP-13 testing. Design criteria established werr as follows:

Feed rate: 5 TPH
Loading: 0.5(lbs of solid waste/lbs of air)
Air classifier velocity: 1300 fpm
Blower design point: 6800 scfm, 9 in. w.g., 22hp

Conclusions

The following conclusions were made from the results of LP-11 testing series:

1. Shredding and air classification operations on municipal solid waste produce a fuel form having very satisfactory physical properties for energy recovery through combustion in a fluidized bed reactor. A solid waste handling subsystem with reliable components has been developed and extensively operated.
2. The vertical fluidized bed combustor has again been shown to be a highly efficient, easily fed, readily controlled reactor of simple design that is capable of utilizing low quality fuels.
3. Results of low pressure operation of the waste-fired vertical fluidized bed combustor during the testing series showed an average combustion efficiency of 99.7 percent.
4. Test results showed no problem with fluidized bed residue buildup. No bed material agglomeration was experienced in the 1270 - 1450° F bed temperature range.

5. Gas phase combustion above the fluidized bed was again within acceptable values.
6. Combustor freeboard and exhaust system deposit problems due to the aluminum content of solid waste have been solved.
7. The addition of the spinner duct in the first stage separator greatly reduce the formation of clinkers at the initial gas impact point.
8. The capability of the separator material removal systems to continuously remove and transport sand and ash residue material from the bottom of the separators to an external collection point was successfully demonstrated.
9. While the newly installed pneumatic vibrators were effectively preventing ash buildup in the hoppers of the inertial separators, problems of long term inertial separator performance degradation have been encountered due to the tube plugging, particularly in the final stage with very fine hot fly ash. Remedial development work will continue at the more promising high pressure conditions associated with integration into the gas turbine cycle.
10. Exhaust gas sampling instruments again indicated that the pollution control effort required for the gaseous components of the CPU-400 process can be expected to be minimal.
11. No evidence of serious hot gas subsystem material corrosion or erosion problems has been found.
12. The capability of the computerized central system to adequately control low pressure pilot plant operation was successfully demonstrated.

SECTION VI

TURBO-ELECTRIC SYSTEM

This section discusses the design and procurement of a turbo-electric system for the high pressure configuration of the CPU-400 pilot plant, and summarizes the results of a survey of candidate turbines for the CPU-400 prototype plant. The pilot plant turbo-electric system was designed and procured under contract tasks HP-1 and HP-2, respectively. The prototype turbine survey was performed under contract task PL-2.

DESIGN AND PROCUREMENT OF THE TURBO-ELECTRIC SYSTEM

The turbo-electric system compresses the air used in the combustion process, uses the combustion product gases to develop turbine shaft power to drive the compressor and the power generator, and then generates and controls electric power output. The turbo-electric system consists of a 1000 kW turbine-driven generator, the switchgear and electric load banks needed to absorb the generated power, and the inlet and outlet piping necessary to mate the turbine to the hot gas interface.

The basic components of this system have been predominantly supplied by Mid-Continent-Ruston as a packaged turbo-electric unit. The design and installation of the turbine and the generator and switchgear into a skid-mounted assembly, were accomplished by Mid-Continent Supply Company. When delivered, the turbine system was modified sufficiently to install the turbine combustor in a remote location, and to connect the solid waste combustor and separators to the turbine. The electric load bank and light bank, supplied by another contractor, were also added to the turbo-electric unit.

Turbo-Generator Selection

The criteria for the selection of the CPU-400 pilot plant gas turbine-generator were predicated on the results of system engineering studies performed under contracts PH 86-68-198 and 68-03-0054. From these studies it was concluded that, as far as possible, the pilot plant gas turbine-generator should be sized to mate with the existing pilot plant combustor, and should be a readily available, standard production unit requiring only slight modification for use with the pilot plant hot gas system. Most important, the turbine had to be an open cycle, constant pressure machine, designed with an external combustion chamber and an external compressed air duct. The pilot plant combustor had been sized for a 1500 hp gas turbine-generator that would produce approximately 1000 kW of electrical power, essentially one-tenth the power output of the full scale CPU-400 at full flow conditions. Also, in order to avoid excess fluid bed maintenance problems, its inlet temperature had to be maintained under 1500° F; this limited the choice of turbines to those with turbine inlet temperatures in the 1400°F to 1500°F operating range.

A review of the available turbines indicated that the Mid-Continent-Ruston TA 1500 gas turbine best met these criteria. It was found to be a well constructed heavy duty unit, amenable to experimental work; it was reasonably priced; it had an acceptable delivery schedule; and it was designed for use with an external combustor. The Ruston turbine inlet temperature and compressor pressure output ratings matched the temperature limits and operating pressure requirements of the pilot plant combustor, and a 1000 kW generator was supplied with the turbine as standard equipment.

Turbine Description

A cutaway drawing of the Ruston TA 1500 turbine configuration as normally supplied by Mid-Continent Supply Company is shown in Figure 6-1. The turbine combustor is shown in its standard position with a cross-over duct removed to permit a view of the rotary components. The cross-over duct is normally connected between the compressor outlet flange, shown in the background, and the rectangular combustor flange, shown in the foreground.

The turbine consists of a gas generator assembly and a power assembly. Included in the gas generator assembly are a 13-stage compressor, a combustion chamber, and a compressor-driven turbine. A low pressure turbine and a gear box comprise the power assembly. Both assemblies

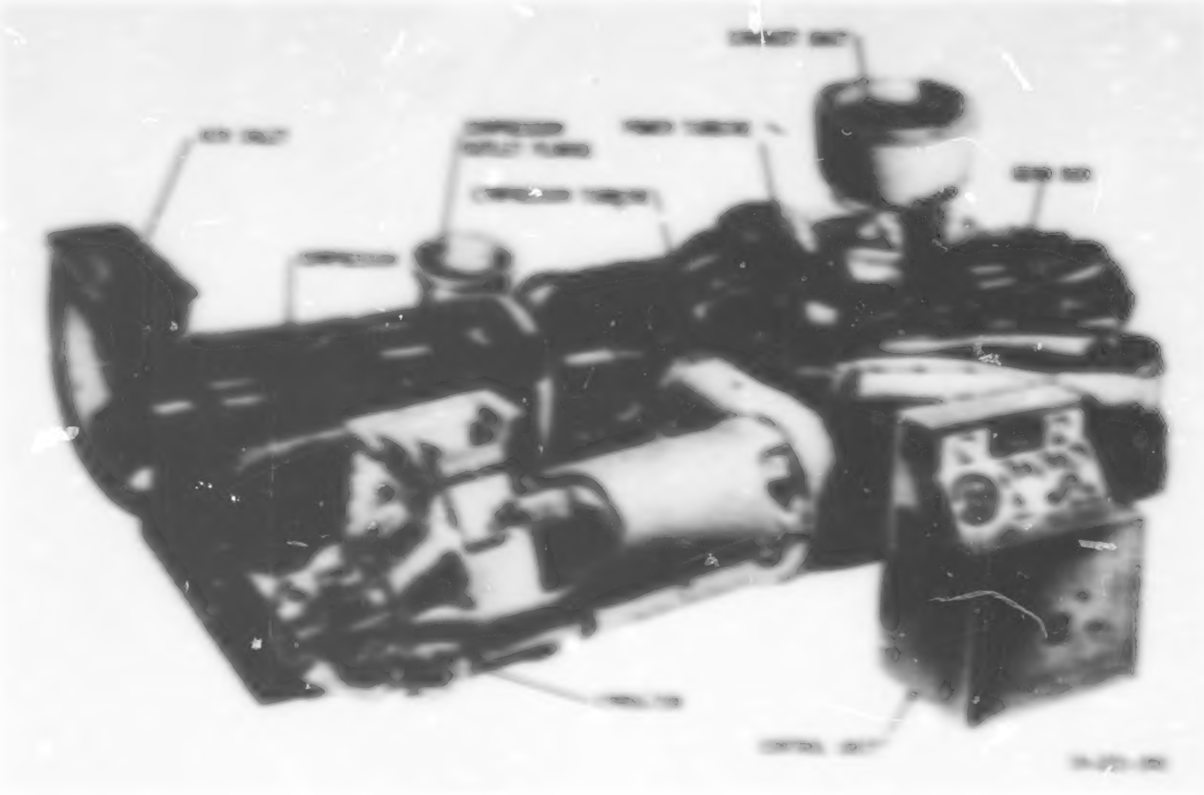


Figure 6-2 Ruston TA-1500 Gas Turbine

are independent of one another and either one may be dismantled without interfering with the other. The combustion chamber can also be removed without disturbance of the other components. Details of the turbine, as installed in the pilot plant facility, are shown in Figure 6-2.

During operation, air at atmospheric temperature and pressure is drawn into the 13-stage compressor through an air filter. As the air passes through the compressor, the moving blades produce a rise in pressure and increase the velocity of the air. The stator blades then convert some of the increased air velocity into a further increase in pressure. The compressor rotates at a nominal 11,000 rpm and compresses 23 lb/sec of air to about 65 psig (80 psia), the maximum pressure it will reach throughout the complete cycle.

From the compressor outlet, the high pressure air is ducted to the combustion chamber where heat energy is added by the burning of the fuel. In this environment the gas volume has been greatly increased without a change in pressure, and the gas temperature reaches the maximum limit (approximately 1450°F) it will attain throughout the complete cycle.

From the fusion combustor the hot gas is ducted to the compressor turbine where a portion of its heat and pressure energy is expended in driving the compressor turbine. The entire output of this turbine is used to drive the compressor. This combined unit acts as a gas producer to the power turbine, and automatically raises or lowers the

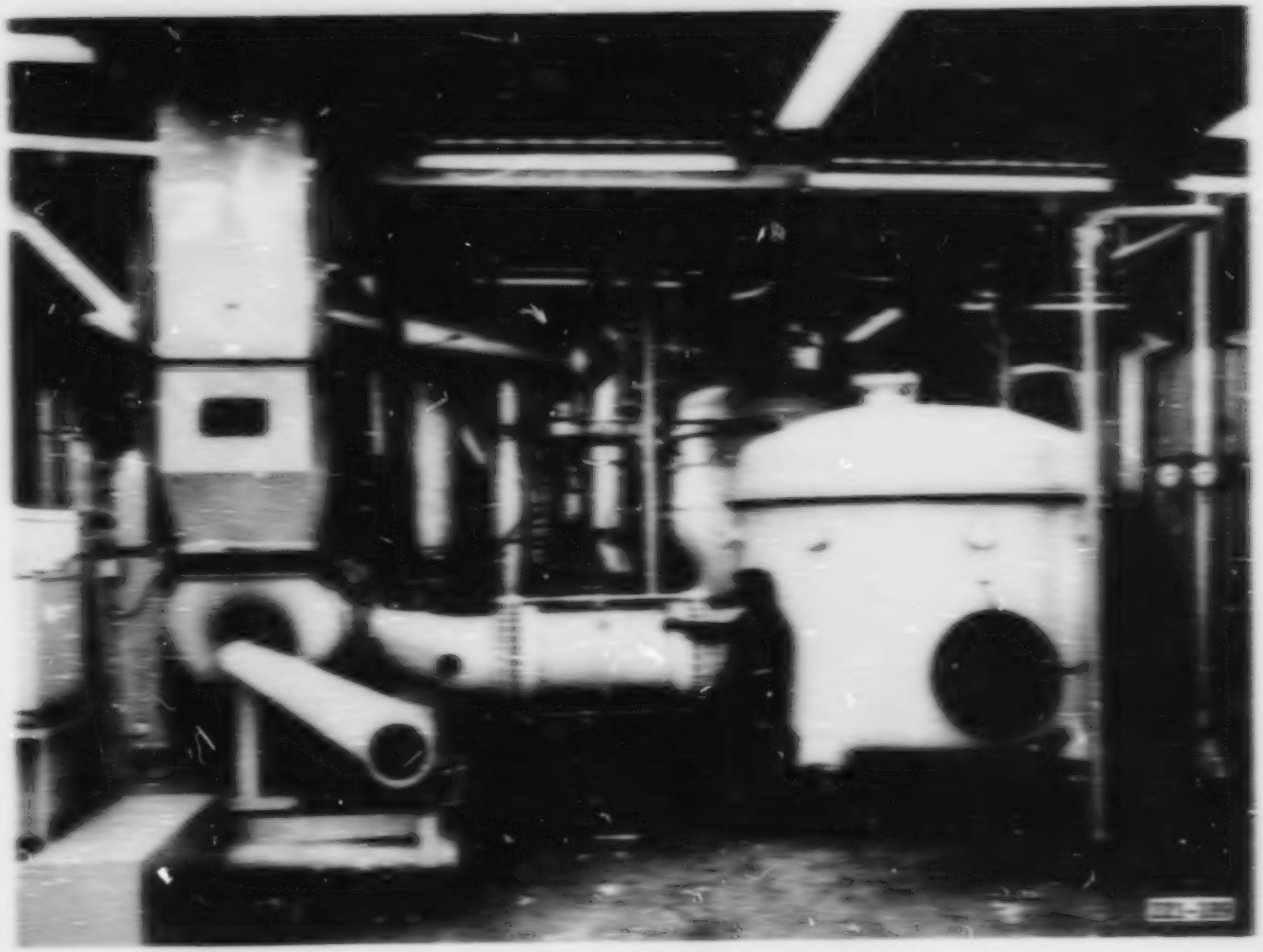


Figure 6-2 Turbine Installation into the CPU-400 Pilot Plant

cycle pressure and maximum gas temperature in accordance with the power required at the output shaft.

With the temperature and pressure having dropped considerably, the gas flows to the power turbine, where some of its remaining heat energy and a large portion of its pressure energy is converted into useful power at the output shaft. This is achieved by expanding the gas down to atmospheric pressure before it leaves the turbine and is discharged to the atmosphere. The output shaft rotates at 6000 rpm and delivers approximately 1500 hp into a speed reducing gearbox, the output shaft of which rotates at 1800 rpm.

Power Generator

An Electric Machinery Company Model BEMAC II electric power generator is coupled to the turbine gearbox output shaft. The generator is a 3-phase, 60 HZ alternating current machine rated 1250 kW at 480 volts. Although its maximum rating is 1250 kW, it generates a nominal 1000 kW in the pilot plant.

Switch Gear

The switchgear used to monitor the generator output and to couple the generator to the load and lamp banks is standard equipment supplied by Mid-Continent Controls. It is housed in a metal enclosure and consists of an a.c. ammeter, a voltmeter, a wattmeter, and a frequency meter for indication of power generating conditions. Also included is a manually operated 3 pole air circuit breaker with a 1600 ampere, 600 volt rated capacity and a 50 kilo ampere interrupting capacity. Equipment for ground detection and generator winding temperatures are also incorporated. The switchgear, as installed in the pilot plant facility, is shown in Figure 6-3.

Load Banks

A resistance load bank and a lamp load bank are used in dissipating the generator output power.

Resistance Load Bank-

The resistance load bank is a forced air-cooled unit with a blower supplying air to a plenum chamber containing the resistors. The assembly is installed indoors and is provided with a hood for exhausting air to the outdoors through the building roof. The load bank is rated at 1150 kW for dissipating the 1000 kW working output of the generator at unity power factor. The resistors are controlled individually by means of remotely operated contactors which provide load selection in fourteen 75 kW coarse steps and the balance in four 25 kW fine steps.

Lamp Load Bank-

The lamp load bank consists of two wall mounted units, each containing eight lamps. Lamp spacing is based on ambient cooling with a maximum power rating of 1.5 kW for each lamp. However, lamp ratings can be reduced to a minimum of 500 watts. Each light bank is controlled remotely by a single contactor.

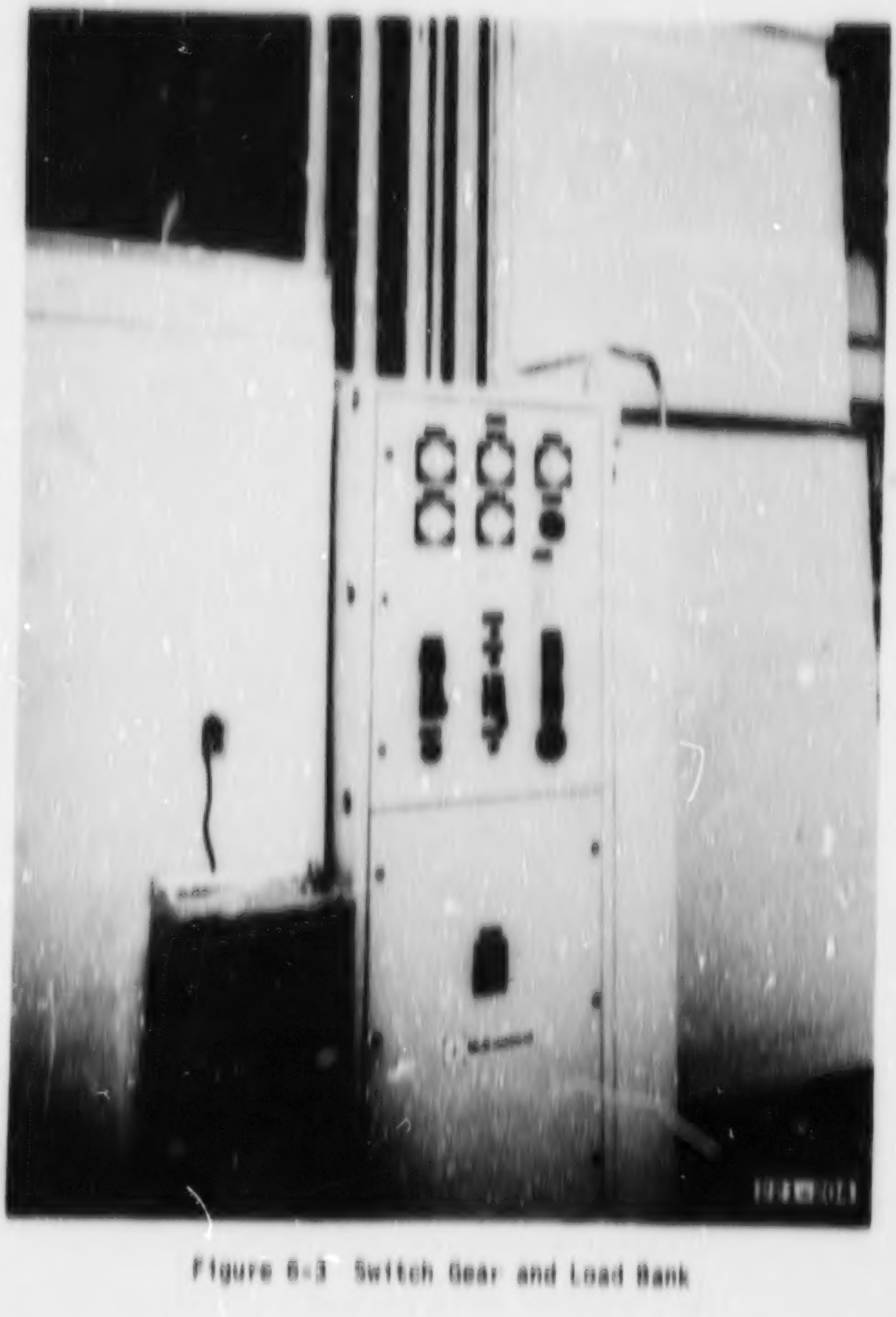


Figure 6-3 Switch Gear and Load Bank

Piping and Control Design Considerations

The thermal energy source for driving the turbine is obtained from a parallel gas flow system that contains a diesel fuel burning combustor in one path and a solid waste burning combustor followed by three stages of particle separators in the other flow path. Two basic problems inherent with the unique design of this subsystem were: 1) the design of the interconnecting piping to handle hot gases at temperatures up to 1500° F while allowing for linear thermal expansion without developing excess loads on the turbine flanges; and 2) the selection of control methods and operating techniques to start and operate the turbo-electric system with a large volume, optional combustor energy source between the compressor and turbine. The following paragraphs discuss the design philosophy used in solving these problems.

Hot and Cold Piping Design-

The terms "hot" and "cold" are used in reference to the gas temperatures within the piping runs between the combustors and the turbine inlet and the piping runs between compressor outlet and combustor inlets, respectively. The hot and cold piping runs are depicted in Figures 6-4 and 6-5.

Hot Piping Design - Pressure piping is being protected from high temperature gases by internally insulating with Kaowool and lining the hot gas piping with heat resistant stainless steel. Due to this insulation, the hot gas piping metal skin temperatures are approximately 400° F.

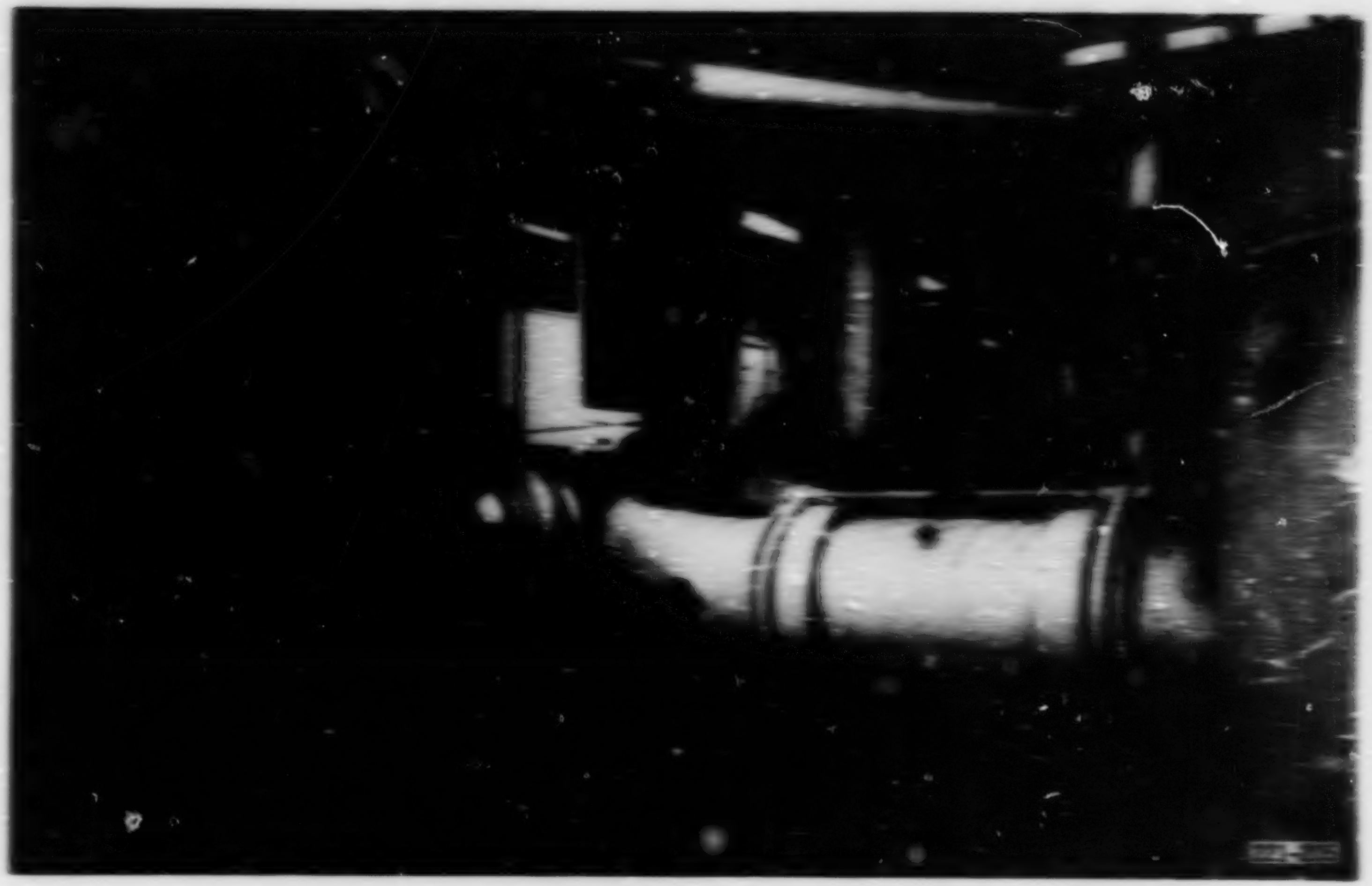
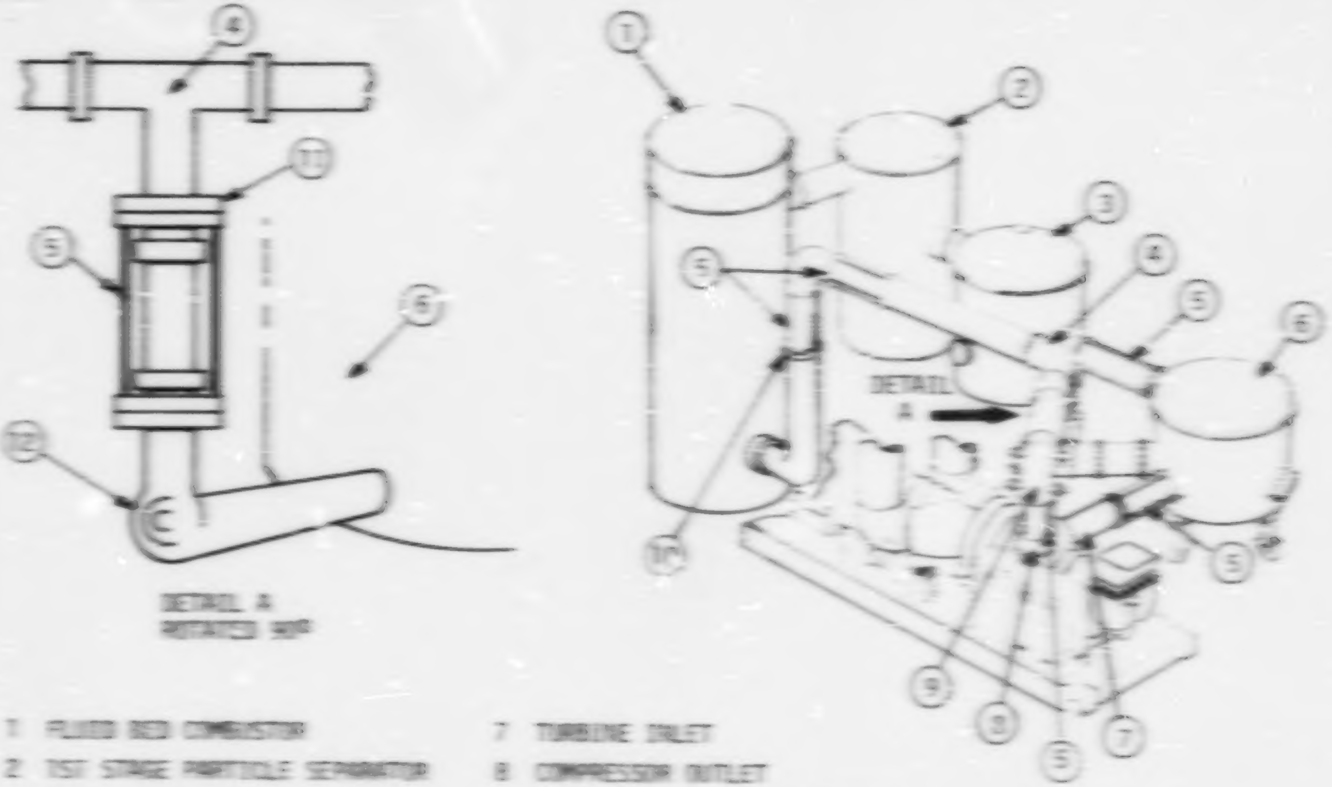


Figure 6-4 Compressor Line Piping with Valves to the Fluid Bed Combustor


4
11
5
6
12
DETAIL A
ROTATED 90°
1
2
3
5
4
5
6
DETAIL
A
10
5
9
8
5
7

1 FLUID BED COMBUSTOR
2 1ST STAGE PARTICLE SEPARATOR
3 2ND STAGE PARTICLE SEPARATOR
4 TEE
5 EXPANSION JOINT ASSEMBLY
6 3rd STAGE PARTICLE SEPARATOR
7 TURBINE INLET
8 COMPRESSOR OUTLET
9 ELBOW AND EXPANSION BELLOWS
10 AIR INLET VALVE (003)
11 AIR INLET VALVE (012)
12 RUSTON COMBUSTOR

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Figure 6-5 Hot and Cold Pressure Piping Runs

Linear expansion of the piping is accommodated by the use of bellows expansion joint assemblies where required to prevent excessive turbine flange loading. All the expansion joints used are tied with stress rods so they do not expand axially, but do allow a lateral motion of from ½ to 1 inch.

The thermal expansion between the combustor and third stage separator results in a lateral deflection of the expansion joint downstream of the separators. The thermal expansion between the separators and the turbine results in a lateral deflection of the expansion joint between the second and third stage separators. To accommodate these deflections, the particle separators are mounted on casters. Thus, they are fixed in the vertical plane, but are flexible in the horizontal plane.

Cold Piping Design - The cold piping skin temperature can never exceed the 400 F compressor outlet temperature; therefore, insulating the piping was not required, and ordinary carbon steel pipes were used. However, the cold piping design was complicated by three factors: (1) the angular displacement of the horizontal piping runs needed to accommodate the Ruston combustor; (2) the two butterfly valves required to control air flow to the combustors; and (3) the difference in length between the vertical piping at the fluid bed combustor inlet and the verticle piping at the Ruston combustor and turbine compressor.

The expansion design philosophy is identical to that of the hot gas piping if one considers the cold piping joined at the tee over the Ruston combustor as being made up of three L-shaped piping runs.

Each piping run consists of one horizontal leg and one vertical leg and the necessary expansion joint assemblies required to prevent excessive flange loading. As in the hot gas piping all expansion joints are tied with stress rods so that they do not expand axially but do allow lateral motion of from ½ to 1 inch. Thus, the thermal growth in one direction is absorbed by lateral deflections within piping at right angles to the growth direction. These three piping runs are: (1) the piping run between the tee inlet flange and the turbine compressor outlet flange; (2) the piping run from the tee down to the third stage particle separator inlet via the Ruston combustor; and (3) the piping run between the tee outlet flange and the fluid bed combustor inlet flange.

1. The piping run from the tee to the compressor outlet (see Figure 6-4). The horizontal run is mated to an expansion bellows and elbow which is mated to an expansion joint assembly connected to the compressor outlet flange. The thermal expansion in the horizontal run results in lateral deflection of the expansion joint in the vertical run mated to the compressor outlet flange. The corresponding expansion in the vertical leg results in the tee being raised approximately ¼-inch.

2. The piping run from the tee to the third stage particle separator (see detail A, Figure 6-5). The vertical piping in this piping run consists of the tee outlet flange, the flow control valve and

expansion joint assembly, a transition piece, and the Ruston combustor inlet flange. The vertical expansion in this leg is essentially equal to the vertical expansion in the vertical leg mated to the compressor outlet flange. Therefore, the horizontal centerline of the Ruston combustor is at a constant elevation above the floor.

3. The piping from the tee to the fluid bed combustor. (See Figure 6-5). The horizontal piping run from the tee outlet and the vertical piping run from the fluid bed combustor inlet are mated to a curved elbow by two expansion joint assemblies. The expansion in the horizontal run results in lateral deflection of the expansion joint in the vertical leg mated to the fluid bed combustor inlet. The differential expansion caused by the difference in length between this vertical leg and the vertical legs at the compressor and Ruston combustor result in lateral deflection of the expansion joint in the horizontal leg.

Control Considerations-

Control of the Ruston gas turbine is centered around utilizing the existing controls for the turbine and modifying them as required for compatability with the solid waste feed system, solid waste combustor, separators, generator, and load bank. Proportioning of fuel flow into the fluid bed combustor to vary the turbine inlet temperature is used to control power output. Thus variation of the fuel feed rate determines the turbine power output. Computer control of the system will be introduced as the system is developed.

Overspeed Protection - One speed stabilizing and overspeed protection system has been incorporated into the turbo-electric system. Because the pilot plant combustor system contains a large quantity of pressurized hot gas when operating, release of this gas through the turbine can result in very high overspeed conditions for the power turbine generator shaft in the event of an electric load shed. Unrestrained, the resulting high rotary speeds could cause severe physical damage, if not destruction of the generator. To prevent such overspeeds, a disc flywheel inertia, with a dual redundant caliper braking system to apply restraining torque to the flywheel has been added to the generator coupling.

The brake application techniques use compressor duct bleed air as the energy source, and existing Ruston power turbine overspeed control sensing elements for activation. Thus, the gas pressure source that provides the turbine input energy is used as the power source for the brakes. This allows the brakes to be automatically released as the compressor speed drops since the pressure is reduced with lower compressor speeds. The brakes are therefore released at lower speeds when their operation is not required for maintaining speed limits. The braking systems (Figure 6-6) are activated at turbine overspeed conditions of three percent and ten percent.

Three percent overspeed circuit - The three percent overspeed circuit uses the Ruston turbine governor as the speed sensor. If the turbine

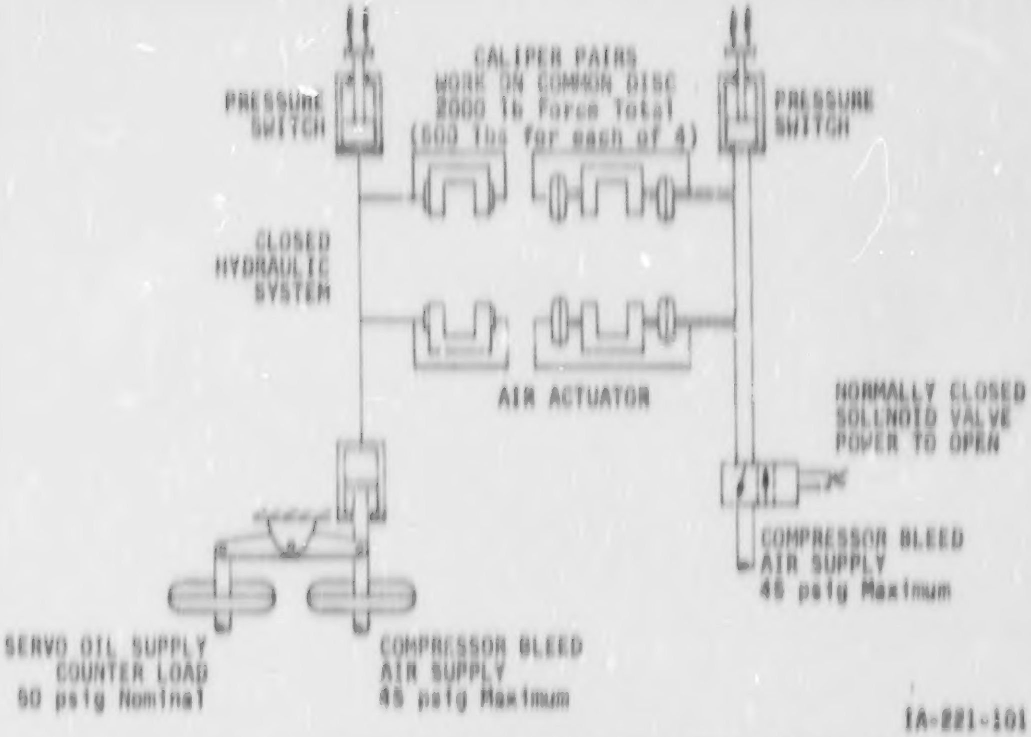
PRESSURE SWITCH
CALIPER PAIRS
WORK ON COMMON DISC
2000 lb Force Total
(500 lbs for each of 4)
PRESSURE SWITCH
CLOSED HYDRAULIC SYSTEM
AIR ACTUATOR
NORMALLY CLOSED
SOLENOID VALVE
POWER TO OPEN
COMPRESSOR BLEED
AIR SUPPLY
45 psig Maximum
SERVO OIL SUPPLY
COUNTER LOAD
60 psig Nominal
COMPRESSOR BLEED
AIR SUPPLY
45 psig Maximum
IA-221-101

Figure 6-6 Generator Shaft Braking System Schematic

speed increases to a level greater than three percent over the governor setpoint, two redundant microswitches are actuated. These microswitches in turn energize three solenoid valves. Two parallel redundant valves exhaust the compressor air that holds the dump valves closed. The dump valves then open and exhaust a portion of the compressor output flow, thereby reducing the energy available to the turbine. The third solenoid opens compressor air to one pair of disc brakes on the edge of the turbine inertia disc, thereby absorbing energy. The microswitches are released as soon as the speed drops to a value less than three percent over the governor setpoint. This in turn allows the dump valves to close and the disc brakes to be released.

Ten percent overspeed circuit - A ten percent overspeed circuit uses an unbalanced rotating weight in the gear box as the speed sensor. If the turbine speed exceeds ten percent of the design speed for the system (independent of any setpoint), the rotating weight shifts off center and trips a valve, causing the compressor air holding the dump valves closed to be vented and also causing servo pressure to be exhausted. The venting of the air to the dump valves allows them to open, releasing a portion of compressor air as in the case of the three percent overspeed operation (note that the three percent overspeed switch should have already caused the dump valves to be opened, thereby making the operation redundant). The loss of servo pressure causes the two other energy absorbing systems to come into operation. One is a set of disc brakes (besides the three percent overspeed disc brake units) that are energized by compressor air but restrained from actuation by servo oil pressure. The second system brought into operation is the load bank. Loss of servo pressure causes pressure switches to be actuated which in turn energize all 75 kW resistors in the load bank, thereby loading down the generator.

The valve that is tripped by the ten percent overspeed is not automatically reset, but requires manual resetting. The system will therefore be completely shut down and require a complete restart to come back on-line following a ten percent overspeed condition.

SURVEY OF CANDIDATE TURBINES FOR THE CPU-400 PROTOTYPE PLANT

Since the development of a new gas turbine and associated hardware would compound the operating risks and inflate the prototype cost, the turbine survey was limited to existing industrial gas turbines with proven operating reliability and design characteristics. Nine candidate turbines sized in power output from 2 to 20 megawatts were evaluated for performance with a solid waste combustion system, and for costs of purchasing, installation, and operation. The 2 and 20 megawatt size extremes corresponded to solid waste throughput rates of 120 to 1200 tons per day, respectively, and were based on an 80 percent utilization factor. Thus, allowing 6 pounds per day of solid waste per person, the candidate turbines covered a nearly tenfold capacity range that would handle solid waste from municipalities with corresponding populations of approximately 40,000 to 400,000 persons. Both performance and cost data resulting from this evaluation are shown in Table 6-1.

Table 6-1. TURBO-ELECTRIC SYSTEM CANDIDATE SUMMARY

Parameter	Manufacturer / Model								
	General Electric			Solar	Westinghouse			[illegible]	
	[illegible]	[illegible]	[illegible]	Centaur	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
System rating (MW)	7.80	19.51	27.74	2.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] flow (lb/hr)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
" " " [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Specific consumption [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Turbo-generator price	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total installed cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Capital cost per kW ($/kW)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Annual operating costs ($/yr)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Periodic maintenance cost (once each 3 years)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Electric power annual revenue	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Annual savings for [illegible] power	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total annual return	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The system ratings given in the table are as-installed with allowances for installation effects. The turbo-generator prices shown were provided by the manufacturers as estimated values. The total installation costs were obtained by estimating modification and installation costs, then adding this to the purchase price. All other costs and revenues are estimated values without firm quotations or detailed designs to support them; however, they are felt to be reasonable and conservative values. Operating costs and revenues that are functions of system running time are based on 7,000 hours or 80 percent utilization per year.

All of the systems covered by the Table 6-1 data involve one turbine of the model indicated at the top of each column. This study explored the performance and costs associated with a broad range of capacities from 2 to 20 megawatts in single turbine systems only. Because of this limitation, two factors tend to cause the lower capacity systems to be more expensive to buy and operate on a per kilowatt or per solid waste ton basis. The first factor is the economics of scale in manufacture of the larger gas turbines. As the data shows, the capital cost per kilowatt capacity is lower for the larger machines. It varies from a low of $116.40 per kilowatt for the 15.39 megawatt W191G turbine to a high of $318.04 per kilowatt for the 3.74 megawatt W41G turbine. The second factor is that the operating labor costs are treated as being the same for each system, since it is likely that the same number of operating personnel will be required for around-the-clock, 7 days a week operation of each independent system, regardless of its capacity. This imposes a rather severe but realistic penalty on a single turbine system under 5 megawatts in capacity. Thus, the net annual dollar return for turbo-electric systems under about 300 tons per day combustion capacity reduces to negative dollars (costs) or at best zero return.

The data indicated one significant general conclusion: to obtain the greatest dollar benefits from the turbo-electric system using a single turbine unit, the solid waste combustion capacity should be sized greater than about 500 tons per day. Sizing the plant greater than about 700 tons per day combustion capacity provides decreasing returns for the turbo-electric system. This conclusion applies only to the turbo-electric subsystem and does not incorporate cost and return trends associated with the solid waste handling or solid waste combustion subsystems involved in a total CPU-400 system. Therefore, the optimum sizing of a total plant could shift away from the capacities mentioned above due to the other subsystem effects. However, since the scope of this study was limited to evaluating turbo-electric systems only, the analysis of the other CPU-400 major subsystem effects on total system costs and returns were not included. Such considerations are appropriate to a more comprehensive evaluation document or to those design studies and proposals dealing with a unique installation where requirements are more firmly established.

It should also be pointed out that CPU-400 systems need not be restricted to single turbine units for the larger capacity installations. Considerations of operating flexibility, reliability, maintenance ease, labor cost reduction, and add-on plant expansion capability may favor the use of several smaller turbine modules rather than one large unit. For example, the use of three or four Centaur turbines with reasonable capital costs per kilowatt capacity could provide a 400 to 600 ton combustion capacity plant competitive with a single large unit installation; and provide greater operating flexibility and potentially better reliability.

Further system analysis, performed after this study was completed, resulted in a significant uprating of the solid waste throughput and power generation capabilities of the CPU-400 systems by also burning nondewatered sewage sludge. This uprating, of course, is associated with the increased mass flow going into the turbine on which no compression work was expended. For an existing turbine this uprating is possible only if the area of the turbine nozzle can be increased to compensate for the increased mass flow through the turbine without exceeding the compression ratio design range.

It was established that the nozzle area of the Solar engine could be easily modified for an increase of 12.5 percent. This would result in a power increase to 3 megawatts, its rated level, and a corresponding solid waste throughput increase of 75 percent. This machine is available in a single shaft version with an existing design for a remote combustor, and its air flow rate matches the capacity of the fluid bed combustor now being tested in the pilot plant. Therefore, it is readily adaptable into the pilot plant system. Also, since the pilot plant hot gas system combustor and particle separators are compatible in size to the units proposed for the prototype plant, the use of the Solar engine would minimize the design risks in scaling from pilot plant hardware to prototype hardware.

SECTION VII

REFERENCES

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SECTION VIII

APPENDICES

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APPENDIX A

SOLID WASTE HANDLING SYSTEM

INTRODUCTION

The solid waste handling system configuration used in the CPU-400 pilot plant during the contract period 30 June 1971 to 31 January 1973 was, for the most part, designed during a previous contract. However, the solid waste handling system did undergo some changes during this period in order to provide support for the horizontal combustor testing performed during the LP-1 test series and the vertical combustor testing performed during the LP-8 and LP-11 test series. Most significant of the changes were the incorporation of large 30-inch diameter feeder valves, the improvement of air classifier efficiency, and the design and incorporation of an automated feed control system, thus integrating the entire solid waste feed system with the combustor and pilot plant control system.

In general, all elements of the solid waste system performed adequately to support test objectives. Changes brought about by combustor operating requirements and variations in interface equipment and process variables were accomplished such that in final configuration, predictable performance capability had been achieved.

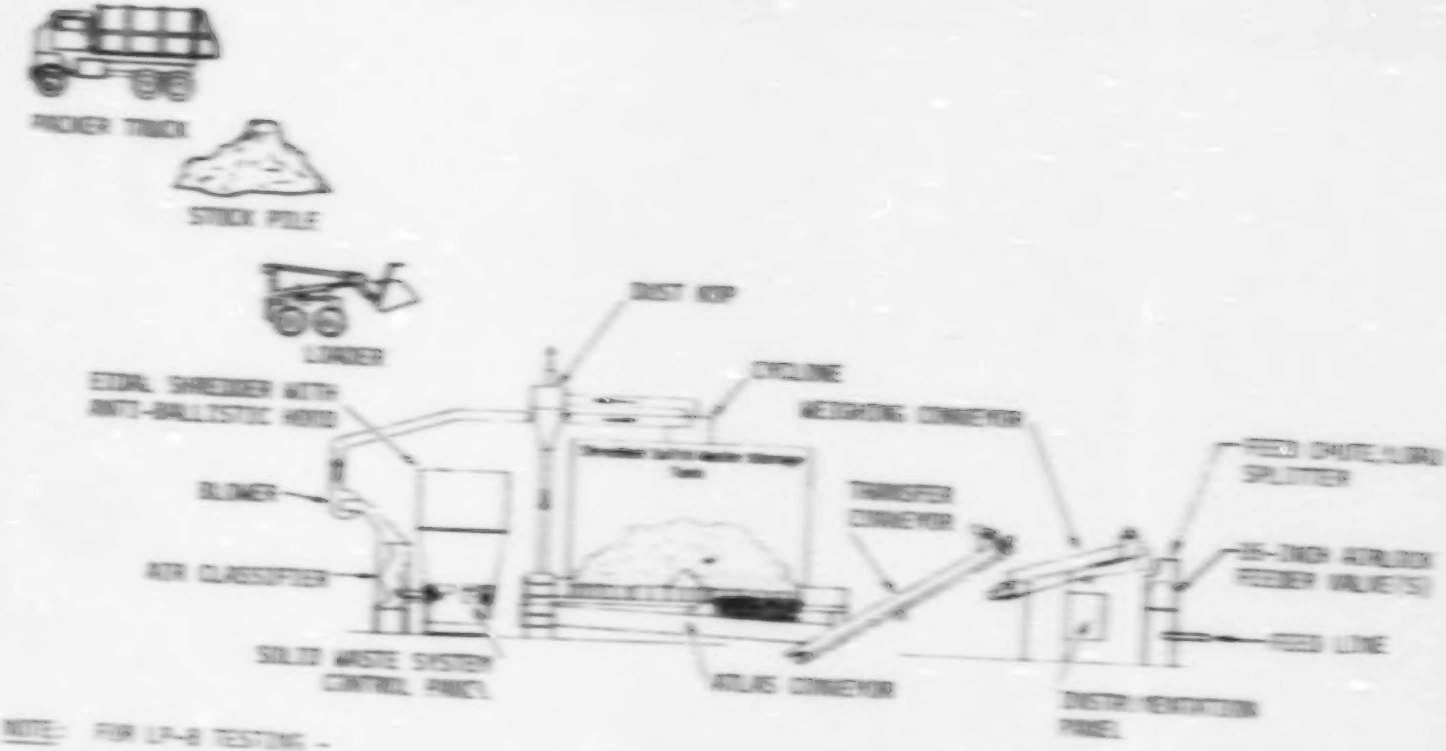
The solid waste handling system as configured to support the pilot plant low pressure test program is composed of two major subsystems - a shredder/air classification/pneumatic transfer subsystem and an Atlas storage/combustor feed subsystem. A diagram of the solid waste handling system used during the LP-I and LP-R testing series is shown in Figure B-1. Figure B-2 depicts the solid waste handling system used during the LP-II testing series.

SHREDDER/AIR CLASSIFICATION/PNEUMATIC TRANSFER SUBSYSTEM

This subsystem consists of equipment and facilities designed to accept and process "as received" solid waste from packer trucks, separate combustibles from non-combustibles, and transfer the combustible fuel fraction to a storage facility for subsequent burning.

Shredder Input Conveyor

Municipal and residential waste delivered by local packer trucks is dumped on the facility floor adjacent to the conveyor in an area capable of accommodating 2 to 3 loads (20,000 to 30,000 pounds). By means of an M-60 Bobcat skip loader with a 15.6 cubic foot bucket, the material is transferred to the hopper of the shredder conveyor to an even depth of approximately 2 feet deep by 4 feet wide. The conveyor assembly consists of a 10 gauge steel and angle fabricated hopper, and a Prab steel belt conveyor with a straight incline of 20 degrees. Thu belt is 48 inches wide, 3/16-inch thick, with a 6-inch pitch and 4-inch high traveling side wings. Pusher flights 4 inches high located on 48-inch centers were removed when experience indicated no advantage was gained and the flight induced fallout of garbage onto the floor. The drive


PACKER TRUCK
STOCK PILE
LOADER
EIDAL SHREDDER WITH ANTI-BALLISTIC HOOD
BLOWER
AIR CLASSIFIER
SOLID WASTE SYSTEM CONTROL PANEL
DUST KOP
CYCLONE
ATLAS CONVEYOR
TRANSFER CONVEYOR
WEIGHING CONVEYOR
FEED CHUTE/LOAD SPLITTER
16-INCH AIRLOCK FEEDER VALVE(S)
FEED LINE
INSTRUMENTATION PANEL

NOTE: FOR LP-8 TESTING -

(a) FEED CHUTE REPLACED BY LOAD SPLITTER

(b) SINGLE FEEDER VALVE AND 6-INCH FEED LINES REPLACED BY TWO VALVES AND 5-INCH FEED LINES

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Figure B-1 Solid Waste Handling System Schematic (LP-7 and LP-8 Testing)

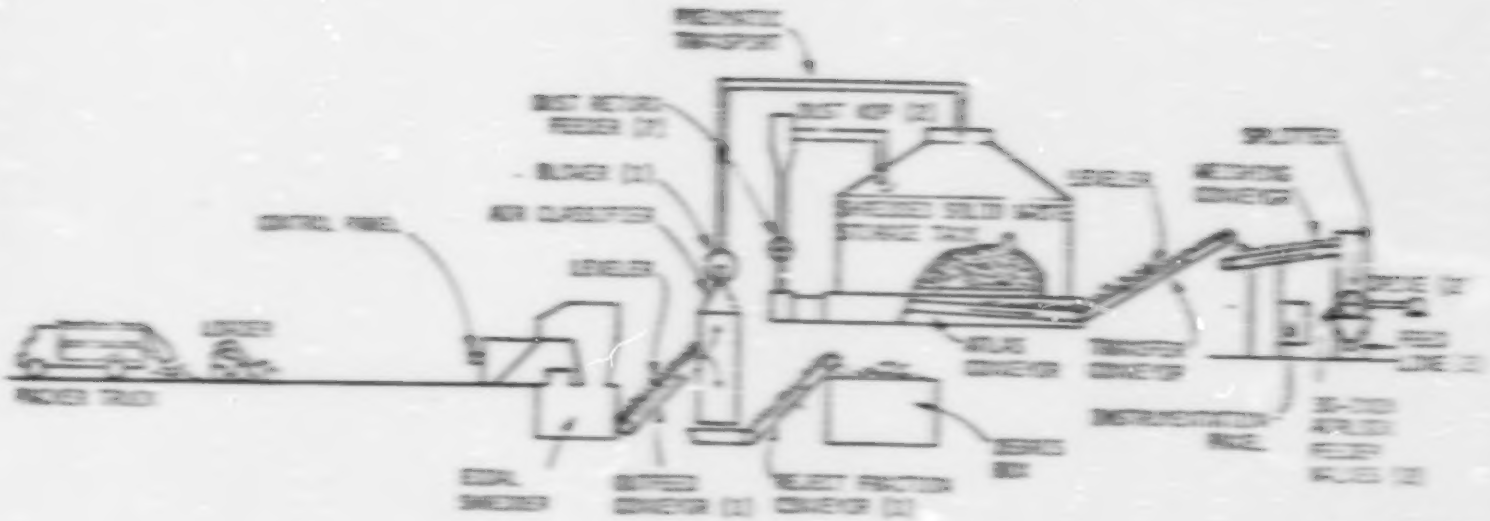

PNEUMATIC TRANSPORT
DUST RETURN FEEDER (2)
BLOWER (1)
AIR CLASSIFIER
CONTROL PANEL
LEVELER
LOADER
PACKER TRUCK
EDAL SHREDDER
OUTFEED CONVEYOR (1)
REJECT FRACTION CONVEYOR (1)
DEBRIS BOX
SHREDDED SOLID WASTE STORAGE TANK
ATLAS CONVEYOR
TRANSFER CONVEYOR
LEVELER
WEIGHING CONVEYOR
SPLITTER
FEED LINE (1)
INSTRUMENTATION PANEL

Figure B-2 Solid Waste Handling System Schematic (LP-II Testing) arrangement has a 3 hp, 230/460 volt, 3-phase, 60 cycle motor with variable speeds from 3 to 18 fpm which can be manually set and then electrically controlled for on/off condition automatically from the control panel by demand current from the shredder. This conveyor dumps solid waste directly into the top of the Eidal shredder, and can easily deliver the waste material at a rate of 2 tons per hour.

Shredder

The Eidal Model 75 mini-mill shredder (Figure B-3) is a patented belt-driven vertical rotor shredder powered by a 75 hp motor. The rotor shaft has double bearings on its lower end, thus it can receive feed over the entire top opening of the shell. The shredder, without feed chute, is approximately 4 feet 6 inches high, 7 feet long, and 4 feet 11 inches wide. The top opening of the shell is 4 feet 4 inches in diameter. An anti-ballistic hood fabricated by CPC encloses the top of the shredder.

The weight of the complete mini-mill without feed chute or feed conveyor is approximately 14,000 pounds with the weight of the rotor at 1800 pounds and the fly wheel weight at 2800 pounds. The unit is equipped with pre-lubricated antifriction bearings, a choker bar to assure a finer grind, a blower and enclosure with filters built around the motor to keep it from picking up dirt and small debris, and a quench water deluge and trickle water source for safety and grind control.

The 75 hp drive motor is of open drip-proof construction suitable for vertical operation. Power requirement is 220/440 60 Hz, 3-phase.

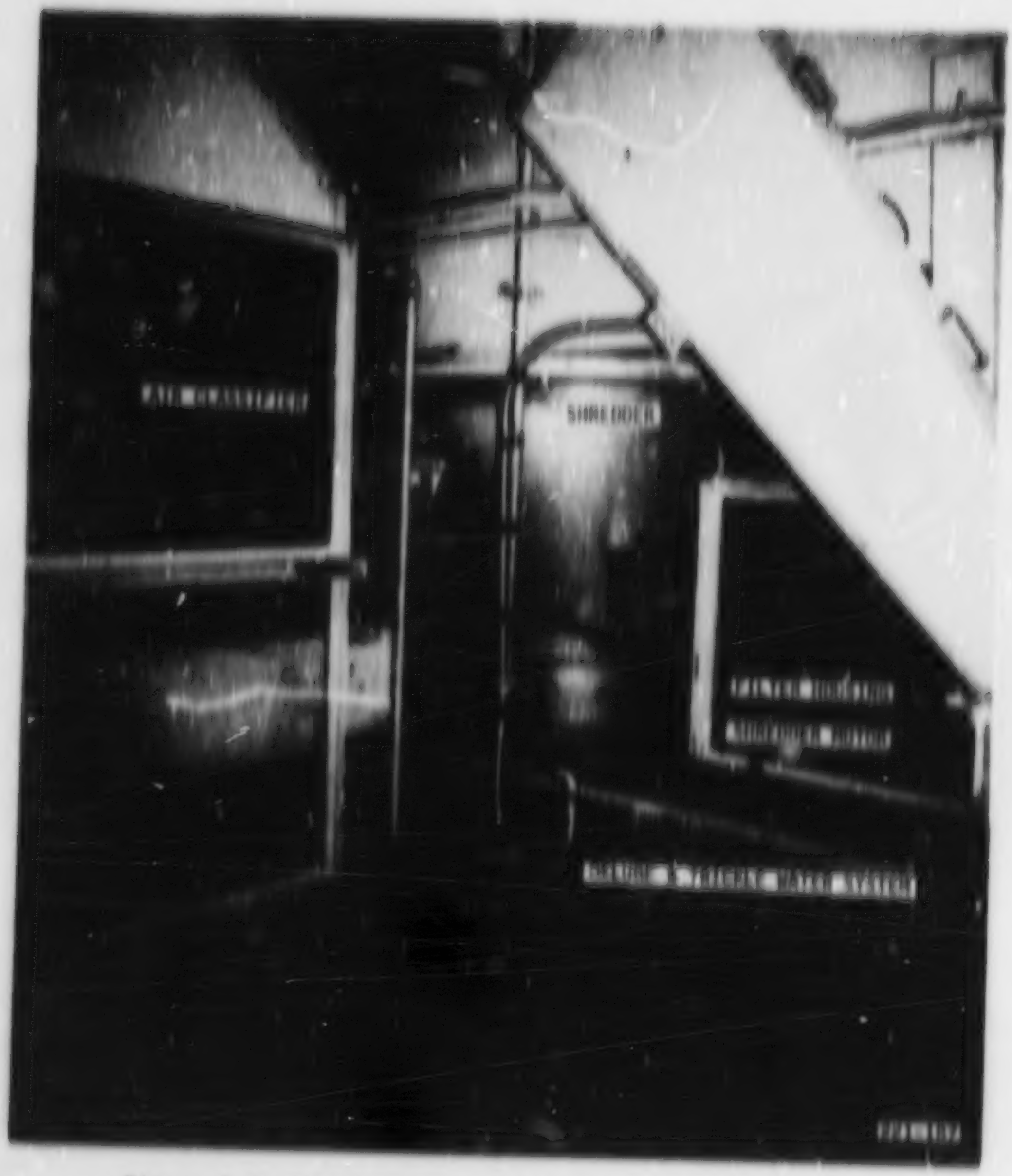

AIR CLASSIFIER
SHREDDER

Figure B-3 Shredder and Air Classifier (LP-1 and LF-8)

During operation, material dumped into the top of the shredder is initially smashed by the top breaker bar and then gradually drops down through a tapered barrel past gear style grinders, becoming smaller and smaller until it passes the choker bar. During the LP-1 and LP-8 testing the shredded waste was then ejected into an exhaust chute, which formed the interface with the air classifier. During the LP-11 testing the shredded material was ejected onto a conveyor which then carried it to the air classifier.

Shredder Outfeed Conveyor

The shredder outfeed conveyor added for the LP-11 testing series is a cleated slider belt conveyor driven by a 3/4 horse power constant speed motor. This conveyor has a straight incline of 30 degrees and is mounted on a 2-foot by 13-foot steel frame. It is equipped with two paddle-type load levelers that maintain a constant level of approximately 3 inches on the conveyor belt. This conveyor is capable of transporting the shredded material at a rate of 2 tons per hour.

Air Classifier

The air classifier separates light combustibles from the heavier metal fractions of shredded waste. Material ejected from the shredder during operation is drawn up a zig-zag path with increasing velocities. Light material including paper, cardboard, light plastics, textile fibers, dirt, etc., are entrained in the main stream and delivered to the pneumatic transfer system. During the LP-1 and LP-8 testing series the heavier materials were allowed to drop out the bottom of the air classifier. The desired cut of material was controlled by adjusting blower rpm. Shop air jets were attached to the exhaust chute of the shredder to allow rapid cleaning of the chute in case a slug of particularly wet material was encountered, which could create temporary blockage of flow into the air classifier. During the LP-11 test series the heavier materials were dropped out onto a reject fraction conveyor for transfer to a debris box.

The air classifier used during the LP-1 and LP-8 testing series (Figure B-3) was a CPC designed and fabricated sheet steel device. The unit was rectangular in cross section with outer dimensions approximately 3 feet wide by 2 feet deep by 5 feet high. The input section was close-coupled to the shredder exhaust chute and the output was on top, coupled to a material transfer pressure blower which induces an air flow of from 4000 to 5000 cfm.

While the operation of this air classifier was satisfactory during the LP-1 test series, the efficiency of this unit during the LP-8 test series was erratic. It was found to be sensitive to variations in solid waste moisture content and composition. This marginal operation of the air classifier led to the design, development and test of a small, conveyor-fed, zig-zag wooden unit followed by a second larger wooden unit (Figure B-4) which subsequently became operational for the LP-11 tests. This unit incorporated movable zig-zag sections which permitted adjustment of the air flow throat width to provide control of separation efficiency for various loading, moisture content and air flow combinations. The overall dimensions of this unit were 16 inches in depth, 30 inches in width, and 96 inches in height. Shredded solid waste was introduced

AIR CLASSIFIER

Figure 8-4 LP-11 Air Classifier

into the upper end via the 2-foot wide shredder outfeed conveyor which in turn was fed directly from the shredder exhaust. As previously mentioned, the reject material from the bottom of the air classifier was transferred to a debris box via the small reject fraction conveyor. The light fuel fraction was exhausted to the Atlas via a 7½-hp Reese materials handling blower.

Reject Fraction Conveyor

The reject fraction conveyor added to the air classifier for the LP-11 testing series is a cleated slider belt conveyor driven by a ½-hp constant speed motor. This conveyor has a straight incline of 30 degrees and is mounted on an 8-inch by 11-foot steel frame. It has the capability of transporting material at a rate of 600 pounds per hour.

Pneumatic Transfer Components

A materials handling blower provides the motive force for pneumatically conveying shredded waste fuel from the air classifier into the Atlas storage unit. A dust control system provides a final air filter before exhausting system pressure to atmosphere.

Blower, Pneumatic Transfer

The blower is a Reese 11 HE steel plate exhauster, 1150 cfm at 16 inches of water gauge complete with 7½ hp, 460 volt, 60 Hz, 3-phase TEFC motor, V belt variable speed drive.

Shredded material enters the air intake duct and is driven by the fan blades into a 12-inch diameter duct connecting to the cyclone located on top of the Atlas storage facility.

Cyclone (Atlas Storage Unit)-

The Atlas storage unit cyclone is located at the top center of the Atlas storage unit, suspended from a bridge structure. The cyclone is fabricated of 10 gauge steel; 44 inches in diameter and 60 inches high with a 24-inch diameter inner chamber, 36 inches high. The inner chamber is fitted at the top with a 24-inch to 10-inch transition adapter which connects to a 10-inch round duct leading to the blower intake of the dust kop cyclone. The storage room cyclone's function is to decelerate and distribute or separate out the shredded waste into the Atlas storage unit. Concurrently, dust and explosive vapors are drawn up through the inner chamber and out to the dust cyclone.

Dust Kop Cyclone-

A single cyclone separator rated at 1200 to 2800 cfm at 10.7 inches of water is located on an elevated (18 feet) platform adjacent to the Atlas storage unit. The unit is supplied by the AGET Manufacturing Company and comprises a series 3000 blower with 10-inch inlet driven by a 7½-hp, 230/460, 3-phase, 60 Hz motor turning at 3600 rpm. Its function is to process dust-laden air from the Atlas storage unit by a principle in which the centrifuging effect of the cyclone, created by rapid rotation of the high velocity airstream, forcibly precipitates dust out of the bottom and into a sealed drum via a 7-inch diameter flexible hose. Cleaned exhaust air then exhausts through the center duct of the cyclone to atmosphere. For LP-8 and LP-11, the dust collected was returned to the Atlas floor via appropriate ducting and a rotary air lock valve.

Subsystem Control

The basic control scheme for the shredder/air classification/pneumatic transfer subsystem was developed under a previous contract and, except for the on/off controls for the motors on the shredder outfeed conveyor and air classifier reject fraction conveyor, which were added for the LP-11 test series, the control scheme remained unchanged during the low pressure testing program.

The active elements in this subsystem consisted of six motors and a solenoid valve. The conveyor motors and shop air solenoid were independent units on different circuits and were operated manually from the central control panel on the shredder conveyor hopper (See Figure B-6).

The shredder hopper conveyor motor was controlled in an on/off fashion based upon the shredder motor current. The levels of this current associated with starting and stopping the conveyor motor were each independently adjustable from the local control panel. The dust kop blower motor and air classifier motor were on a common starter to insure that the classifier is operated only with the dust kop in operation.

Sensors were included to monitor status (on or off) of the shredder hopper conveyor, conveyor and air classifier motors, material level on the shredder hopper conveyor, shredder hopper conveyor speed, and shredder motor current.

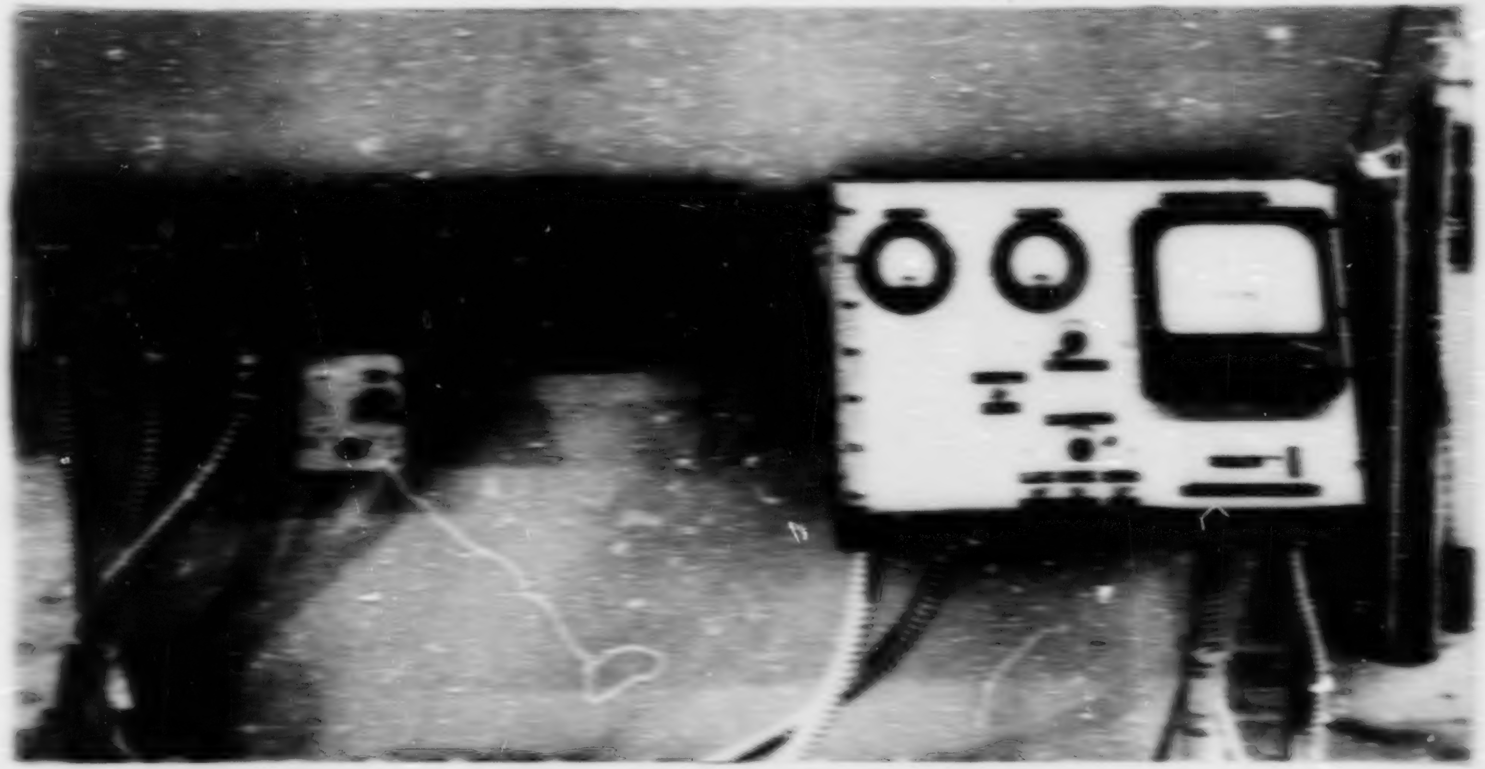


Figure 8-5 Central Control Panel for Shredder/Conveyor/Air Classifier

ATLAS STORAGE/COMBUSTOR FEED SUBSYSTEM

This subsystem provides for the storage of shredded solid waste and an automatic retrieval or outfeed system designed to deliver the desired volume and weight of fuel to satisfy fluid bed combustor demand.

Atlas Storage Unit

This unit is a cylindrical structure 16 feet in diameter and 20 feet tall with a capacity for storing 3400 cubic feet of shredded waste. Recovery rate capability is variable from 100 to 1000 cubic feet/hour. Recovery is accomplished by four chains of sweep buckets located on the floor of the cylindrical bin. Each sweep chain is fixed at one end to a powered rotating "pull ring" encircling the storage area, the other ends being free or trailing. As the pull ring rotates around the periphery of the bin, the sweep chains trail toward the center, contacting the stored material at the outside of the pile, filling the buckets which sweep material onto a single outfeed drag conveyor recessed in the floor (Figure 8-6). At the output end of the outfeed conveyor, transfer conveyors then move the material to the combustor feeder valves.

Sweep Conveyor Drive

The sweep conveyor system is powered by a hydraulic drive package consisting of the Houdaille fixed displacement hydraulic motor, and one power unit consisting of a Vickers variable displacement piston pump coupled to a 7½-hp, 1800 rpm, TEFC, a.c. electric motor. During the LP-8 testing, the efficiency of sweeps was improved by adding an extra

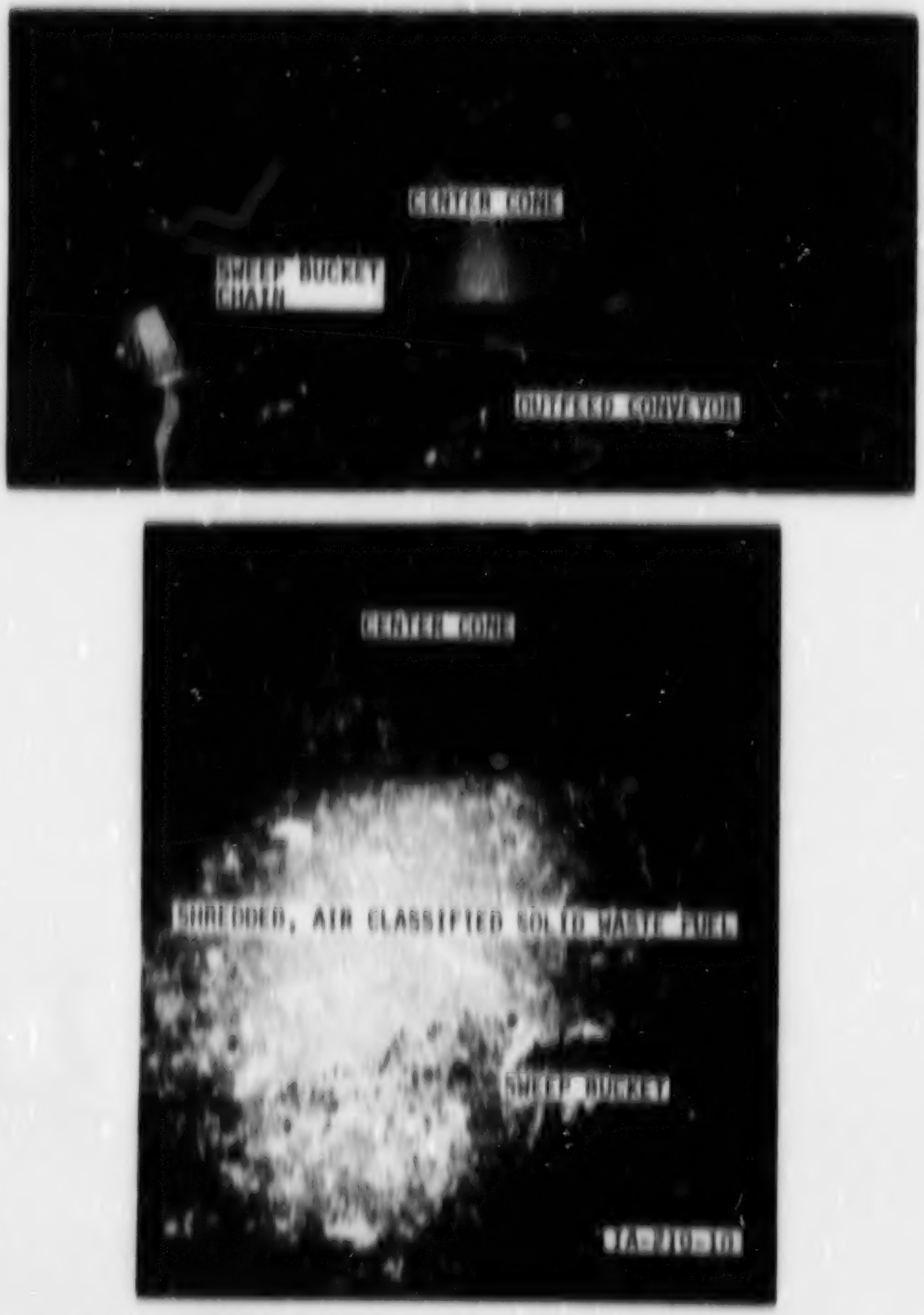

CENTER CONE
SWEEP BUCKET CHAIN
OUTFEED CONVEYOR
CENTER CONE
SHREDDED, AIR CLASSIFIED SOLID WASTE FUEL
SWEEP BUCKET
7A-210-10

Figure 8-6 Photographic Views of the Atlas Storage Unit Interior

bucket to each chain and incorporating digger spikes, and the circum-cyclone inlet, which produced unsymmetrical distribution and localized compacting of fuel, was replaced by a flat, splatter plate which evenly distributed fuel over the Atlas floor. Control is manual at a remote control panel, or automatic through central control room circuitry.

Outfeed Conveyor Drive-

This unit is powered by a hydraulic drive package consisting of one Houdaille fixed displacement hydraulic motor, and one power unit consisting of a Vickers variable displacement piston pump coupled to a 5 hp, 1800 rpm, TEFC, a c electric motor. Control is manual at a remote control panel or automatic through central control room circuitry. Output speeds range from 13.5 rpm to zero. For the LP-8 and LP-11 testing series a rotating clod buster was located at the output end of the conveyor to break up lumps of packed or composted waste.

Control System (AVTEK)

Several modes of operation are available to provide the flexibility required to support large combustor operations or to satisfy lower volume requirements of model combustor tests. Briefly, these modes include:

Mode I	Non-production - Maintenance
Mode II	Manual Speed Control - Direct manual control of sweep drive and outfeed conveyor
Mode III	Manual Volume Demand with Automatic Volume Control - Manually set to desired volume output and then automatically maintained

Mode IV Process Demand with Automatic Volume Control - The "process demand" signal for volume output is supplied from the fluid combustor operational control source (i.e., fluid bed and exhaust temperature)

Constant volume output is controlled through a paddle sensor located on the output end of the outfeed conveyor trench (Figure 8-7). When material level is low in the trench, the paddle sensor signals the volume control system which speeds up the sweeps. As this deficiency is corrected, the sweeps slow down to provide the proper material height in the trench. If, during operation, the stored waste free-flows to fill the trench completely, this condition will stop the sweep system. However, if free-flowing continues, and the trench remains full, the volume outfeed rate will be higher than required. It then becomes necessary to slow the conveyor down to maintain the required volume output. (This is done automatically). As soon as free-flow stops, the system will return to normal operation.

Instrumentation provided to monitor Atlas operation includes: a pressure indicator, located on side wall of Atlas bin to measure internal pressure in inches of water; a demand load indicator, demand volume of solid waste required expressed in percentage of feed rate to the combustor; and an actual load indicator, measured output delivered, expressed in percentage feed rate.

Transfer and Weigh Conveyors

The transfer and weight conveyors (Figure 8-7) carry the waste material

Figure 8-7 Atlas Outfeed Volume Sensor

stored in the Atlas to the feeder valve inlets. During the LP-1 testing series these units were manually controlled from a remote control panel (conveyor motor control panel) located adjacent to the AVTEK. At this time the transfer and weigh conveyors were operated at a constant speed and no synchronization of the speeds of these conveyors with the Atlas sweep speed, feed rate, or the feed volume signal from the pilot plant control room was exercised. During the LP-8 and LP-11 testing, the speed of the transfer and weigh conveyor were controlled by a common variable frequency controller and the ratio of the speeds of these units was then constant. By using the solid waste volume demand signal from the control room as the control signal for the variable frequency unit, the transfer and weigh conveyor speeds became a direct function of the required volume. Therefore, since the commanded volume signal and the level and paddle height signals control the speed of the Atlas outfeed conveyor, a constant level of material is maintained on the transfer and weigh conveyors as a function of the commanded volume signal and the Atlas outfeed conveyor control loop.

Transfer Conveyor:

Material leaving the Atlas outfeed conveyor trench is picked up on a 29 degree inclined conveyor for transfer to a weighing conveyor. The transfer conveyor is a 22-inch wide by 22-feet long belt with 1½-inch cleats on 16-inch centers. It is driven by a 1½-hp gear motor and chain drive. Rotating paddle-like levelers were added for LP-8 and LP-11 to insure constant level of material on the conveyor for more accurate feed rate control.

Weigh Conveyor.

This portable unit is installed between the Atlas transfer conveyor and the combustor feed valve(s) to provide automatic readout and totalized weight of material being fed to the combustor. It is a self-contained, 3600 pounds per hour unit composed of the following standard equipment:

1. 20-inch wide by 12-foot long rubber belt feeder with 1-inch high flange and full length skirt boards.
2. Head pulley drive utilizing a reducer and drive chain driven by a ½ hp, a.c. squirrel cage reversible, induction motor operation on 230/460 volt, 3-phase, 60 cycles.
3. Merrick Model 440 weightometer including: multiple idler suspension; temperature compensated load cell; solid state millivolt to volt amplifier including output indicator and load cell excitation power supply.
4. Running time meter with thumbwheel reset.
5. Solid state mv to v integrator including: rate integrator; seven digit totalizer; zero and span adjustments; test button; impulse transmitter.

The model 440 weightometer is basically a mechanical suspension system which transmits the weight on the conveyor idlers to an electronic load cell. The millivolt output from the load cell is proportional to the material loading on the conveyor per lineal foot of belt. The millivolt signal can be amplified directly or combined with a speed measurement and amplified to produce the desired rate signal. If the conveyor speed is constant, the weight measurement is directly proportional to the rate of material flow on the conveyor belt (pounds per hour).

Load Splitter/Feed Chute

For early, single feeder valve tests performed during the LP-1 test series, a rectangular duct containing a motor-driven serrated wheel was located between the weigh conveyor and the feeder valve to induce separation of input material to each side of the split feed valve. For LP-8 and LP-11 test series, a stainless steel pant leg chute was provided to split the load for two feeder valves. (See Figure B-2).

Feeder Valve(s)

A single, CPC-designed rotary air-lock feeder valve provided the feed mechanism to the horizontal fluid bed combustor tested during the LP-1 test series. The valve body was of welded steel construction and was approximately 16 inches by 30 inches by 30 inches overall dimensions. It incorporated an eight bladed, adjustable tip rotor capable of delivering 30 to 60 pounds per minute of shredded waste to a positive pressure pneumatic conveyor (nominally 3 psi) at a nominal rotational speed of 11 rpm. The original design supplied the full input of shredded waste to a single 6-inch diameter feed line to the combustor (see Figure B-8). Later combustor design changes dictated a requirement for two 5-inch diameter feed lines. This was accommodated in a modification of the valve with installation of divider plates in each of the rotor pockets, thus splitting the valve into two separate sections, each supplying an individual 5-inch feed line (see Figure B-9). The splitter unit mentioned above was accordingly added to aid in splitting

Figure 8-8 16-Inch Air-lock Feeder Valve (LP-1 and LP-8)

Figure 8-9 Air-lock Feeder Valve, Modified for Dual 5-Inch Feed System

the input before it reached the valve. The valve dividers were removed when the system was redesigned to provide two individual low pressure valves for feeding the vertical combustor during the LP-8 test series.

The single valve drive system utilized during the LP-1 test series incorporated a 7.5 hp, 1760 rpm, 230/460 volt, 60 cycle, 3-phase a.c. motor driving a 38.4:1 gear reducer. Output of the reducer to the valve is further reduced from 46 rpm to 11 by sprockets and an ASA No. 100, 2-inch pitch, single width chain assembly. This drive system was replaced by two 20 hp drive/reducer units driving two feeder valves for LP-8 and LP-11 (Figures 8-10 and 8-11).

For the LP-11 test series, two rotary air-lock feeder valves were employed in the system to transfer solid waste fuel from conventional conveyors at ambient pressure to 6-inch pressurized pneumatic transfer lines leading to the fluid bed combustor. The air flow through these lines is controlled by valves 000 and 001. The ESCO Rotofeeders are 30-inch diameter, stainless steel cast valves, utilizing 13 feed pockets with 13 axial sealing edges between the pockets. A typical 30-inch feeder valve installation in the system is depicted in Figure 8-11. The nominal volumetric handling capacity of each valve is 36 cubic feet per minute when rotating at a constant 11 rpm. Each valve is driven through a gear motor unit rated at 20 hp.

Sealing against the pressure is provided by adjustable hardened knife edge blades; four blades on each side of the rotor are continuously sealing against pressure at all times. High pressure air which fills

Figure 8-10 LP-8 Air-lock Feeder Valve and Drive Assembly

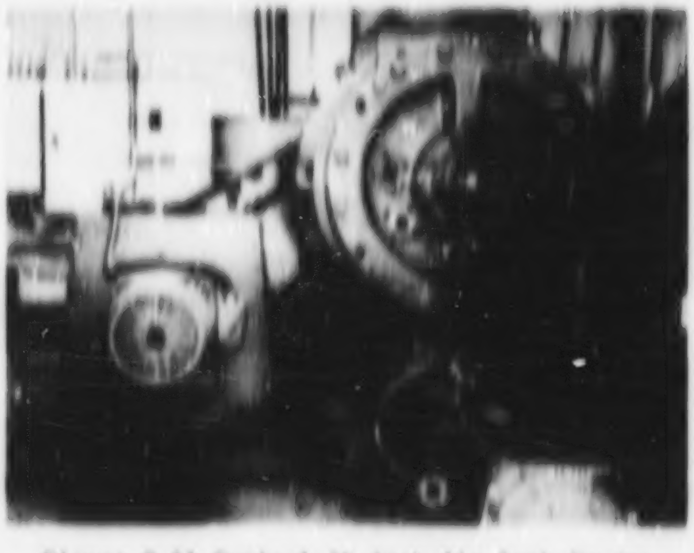


Figure 8-11 Typical 30-inch Air-lock Feeder
Valve and Drive Assembly.

the pockets as they pass through the pressure zone is expanded twice from the high pressure to the low pressure side of the valve before final release to atmosphere. Feed air purge lines assist in blowing solid waste from the pockets as they pass over the valve outlet. To insure concentricity of the valve body, it is water-jacketed and heated to near feed air temperature. This permits closer running clearances and reduces air loss. The rotor shaft bearings consist of graphite impregnated sleeves which are cooled by a water system operating in the 0.2 gpm and 5 to 8 psig range.

Modifications were made to the feeder valves after completion of the low pressure test series to eliminate certain anomalies encountered during these tests. They included: rework of the shaft face seal installation for higher preload and increased floating freedom; rework of drive mount to eliminate chatter and associated resonances with the chain drives; and rework of the transition section between the rotor outlet cavity and the feed pipes.

Subsystem Control

The Atlas storage and combustor feed subsystem contains six motors and one solenoid valve. Originally, during the LP-1 testing, only the motors associated with the Atlas bucket sweeps and Atlas outfeed conveyor were variable speed units. These motors were controlled through the Atlas control unit (AVTEK) and could be controlled either locally at the AVTEK, or remotely by a commanded volume signal from Fisher controllers in the pilot plant control room (Figure 8-12). When operated remotely, the Atlas outfeed conveyor speed is basically a function of the commanded

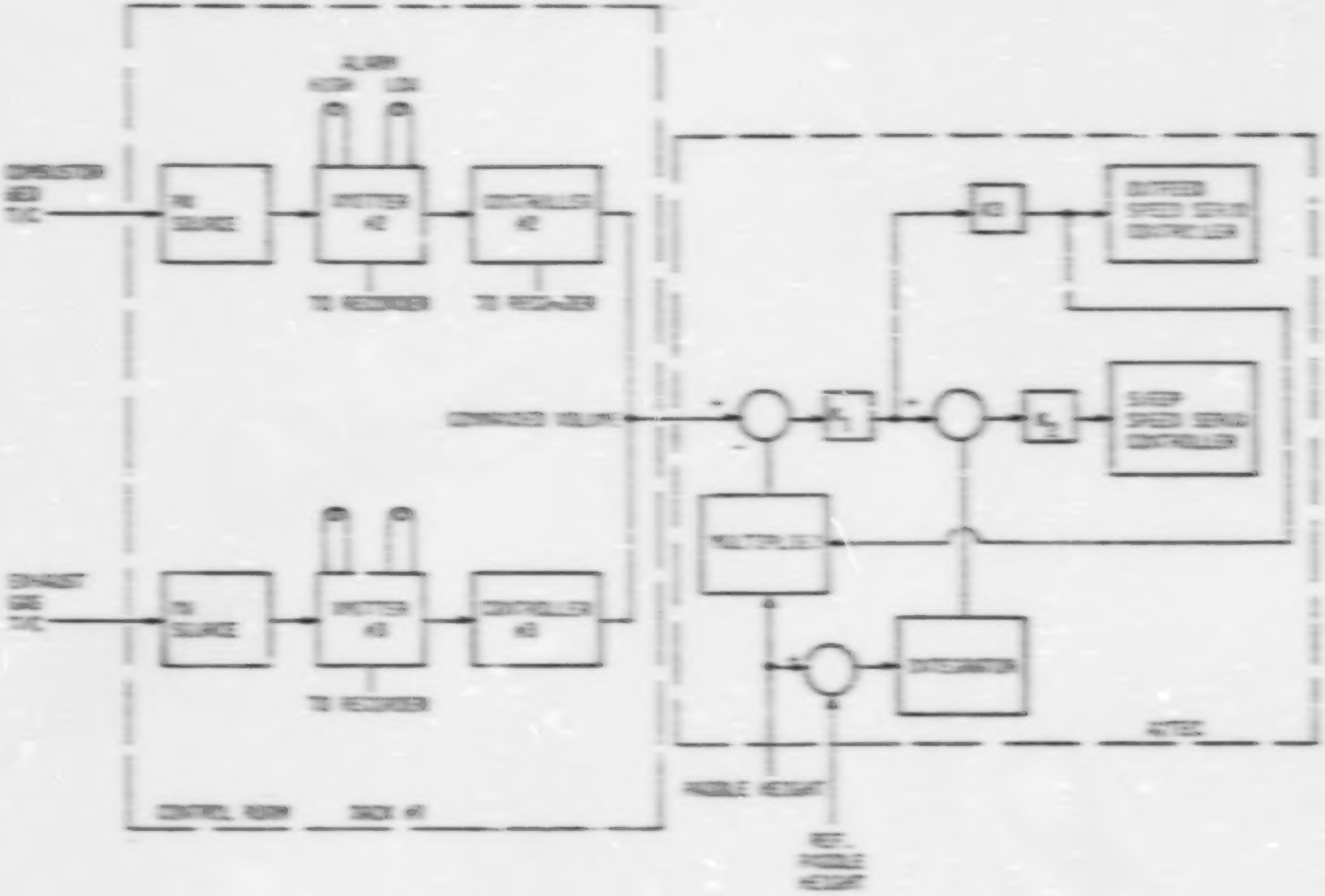

TR-22-4
ALARM
HIGH
LOW
COMBUSTION BED T/C
TH SOURCE
XMITTER #2
CONTROLLER #2
TO RECORDER
TO RECORDER
EXHAUST GAS T/C
TH SOURCE
XMITTER #3
CONTROLLER #3
TO RECORDER
CONTROL ROOM
RACK #1
COMMANDED VOLUME
K_1
K_2
K_3
OUTFEED SPEED SERVO CONTROLLER
SWEEP SPEED SERVO CONTROLLER
MULTIPLIER
INTEGRATOR
PADDLE HEIGHT
REF. PADDLE HEIGHT

Figure 8-12 LP-1 Solid Waste Metering Control

volume and the Atlas sweep bucket speed is controlled by the command along with the error between the desired and actual material height in the outfeed conveyor.

As previously mentioned, for the LP-1 testing the transfer and weigh conveyors were controlled manually from the conveyor control panel located next to the AVTEK, and were operated as constant speed units with no connection to the main pilot plant control circuits. However, during the LP-8 and LP-11 testing the speeds of the transfer and weigh conveyors were controlled by a common variable frequency controller which was controlled by the commanded volume signal routed to it from the input of the AVTEK control loop. The transfer and weigh conveyor speeds were then a direct function of the commanded volume signal, and the commanded volume and Atlas outfeed control loop maintained a constant level of material on these two conveyors. (See Figure B-13).

In this control scheme the motors are automatically operated in a preset sequence. Starting the feeder valve motor causes the weigh and transfer conveyors to be started by powering the variable frequency source. The variable frequency unit contactor then causes the outfeed conveyor motor to be energized which in turn causes the sweep drive to be energized. Loss of any link in the feed metering system causes the motor upstream to be shut down. The solenoid valve operating the lubrication system for the sweeps and outfeed conveyor is slaved to the Atlas controls and requires no special attention.

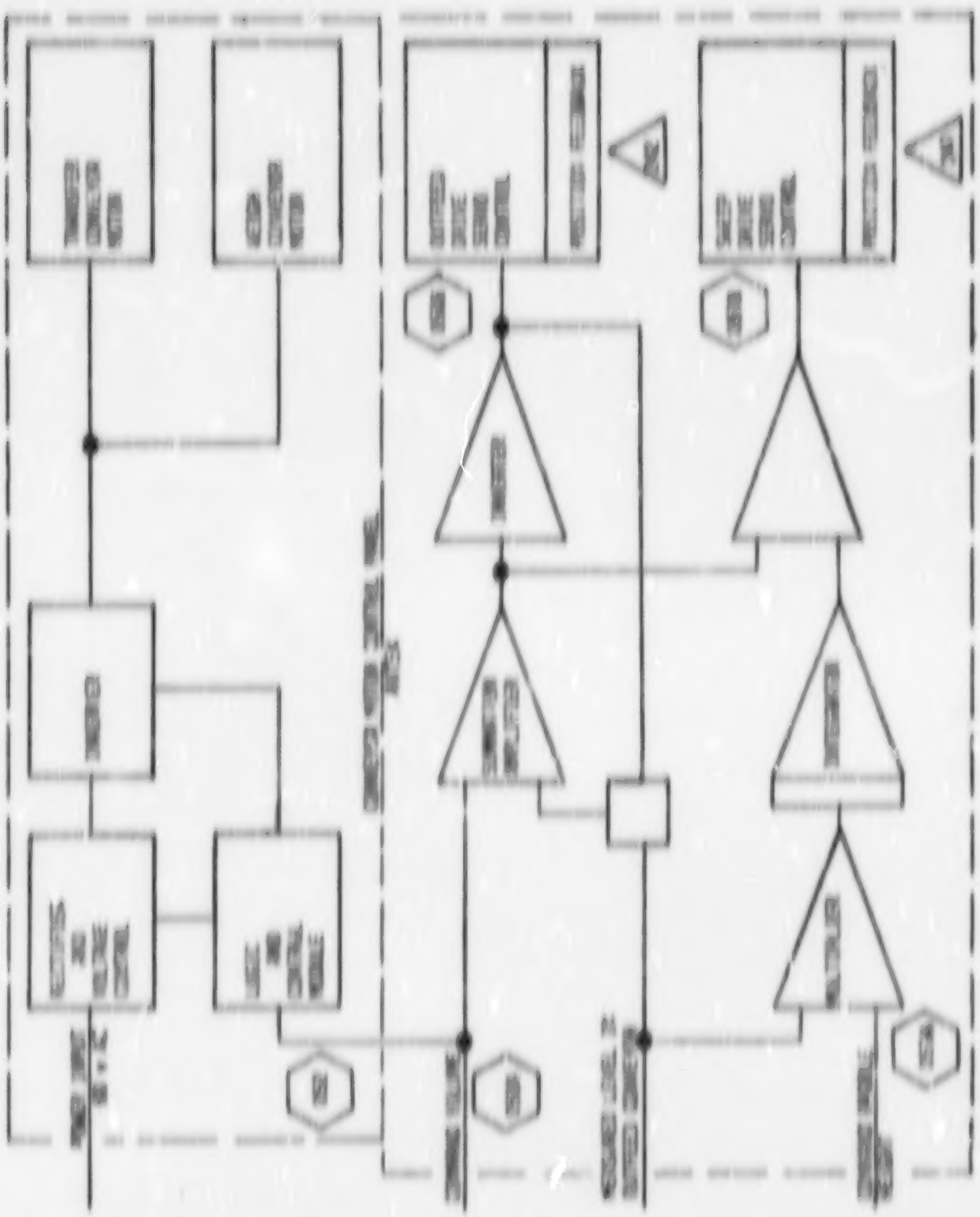


Figure 8-13 LP-8 and LP-11 Solid Waste Feed Control

The solid waste feed rate is controlled by equipment installed in rack 1 in the control room. This equipment incorporates two controllers, a digital temperature indicator, a millivolt source and associated circuitry. At rack 1 the solid waste feed can be controlled either manually or automatically. In manual mode, the demand signal for increased or decreased solid waste feed requires manual adjustment of the controllers through use of thumbwheel settings. In the automatic mode, the desired bed and exhaust temperatures are set into the controllers by setpoints. The controller then compares the actual bed and exhaust temperatures to the setpoints and then either increases or decreases the commanded volume signal based upon the difference between the measurement and the setpoint. The setpoints can be set in locally at the controller, as was done during the LP-8 testing, or it can be set in remotely from the computer, as was done during the LP-11 testing.

APPENDIX B

GAS COMPOSITION AND PARTICLE ANALYSES OF MODEL FLUID BED COMBUSTOR EXHAUST GAS

INTRODUCTION

On July 23, 1971, testing was conducted to establish the chemical qualitative and quantitative composition of the off-gases and fumes from a fluid bed combustor burning municipal solid waste. The results of the test were used to establish the principal corrosive constituents of gases and flyash and their concentrations to permit simulation of the fluid bed exhaust during the turbine blade corrosion-deposition testing subsequently conducted by Westinghouse Research Laboratories.

The Model Number 1 low pressure fluid bed combustor, burning shredded and air classified municipal solid waste, was used to generate the off-gases and flyash particulates which were analyzed by two independent outside laboratories.

DESCRIPTION OF THE ANALYTICAL TECHNIQUES USED FOR THE COLLECTION AND DETERMINATION OF THE OFF-GAS CONSTITUENTS

The Trapelo West Laboratory, contracted by CPC for the outside laboratory support, established a program for analyzing the composition of the combustor off-gas by using mainly wet chemical techniques. In this manner, each gas constituent could be determined at least by one specific method.

Nitrogen, Oxygen and Oxides of Carbon

The Orsat analyzer determined these gases by selective absorption and volumetric measuremnt of the remaining gas volume.

Carbon Dioxide -

Carbon dioxide was measure by bringing the gas sample of known volume into contact with a solution of potassium hydroxide:

$$CO_2 + 2\ KOH \qquad K_2CO_3 + H_2O$$

In the reaction, CO_2 disappeared from the gaseous phase and remained as K_2CO_3 in the liquid phase; hence, the loss in volume of the gas was equal to the CO_2 content.

Carbon Monoxide -

Carbon monoxide was determined by bubbling the gas sample coming from the CO_2 analyzer outlet through an aqueous solution of CuCl. Here the carbon monoxide was oxidized to CO_2 which again was removed as K_2CO_3 effecting another decrease of the original gas sample volume.

Oxygen -

Oxygen was determined by the reaction with pyrogallol (1, 2, 3 - trihydroxy benzene) under alkaline conditions. The end products of the reaction, CO_2 and organic acids, were held as potassium salts in the absorbing solution. Since all CO_2 had been removed from the sample before bringing it into contact with the alkaline pyrogallol, the decrease in sample volume was due to the removal of oxygen.

Nitrogen -

Nitrogen was determined from the balance between original gas sample volume and volume decrease.

Hydrogen

A gas sample collected in a 2.0 liter bottle was brought into the thermal conductivity detector system of a Varian gas chromatograph.

Methane

The gas mixture was spilled from the sampling bottle into the detector system of a Varian gas chromatograph using hydrogen flame ionization detection.

Oxides of Nitrogen

In this test the gas sample was bubbled through a jet impinger (modified Greenberg-Smith impinger or Midget impinger) in which a Saltzman reagent solution of known concentration reacted with NO_2 of the sample changing its color to red. Then the gas was brought into a second impinger containing a potassium permanganate solution to oxidize NO to NO_2 which in return could be detected in a third impinger again by a solution of the Saltzman reagent.

Sulfur Trioxide

Sulfur trioxide was determined by the modified Shell Method. Sulfur trioxide was removed from the sample gas stream by an impinger containing 80 percent isopropyl alcohol and 20 percent water. The sulfur dioxide was collected in the next two impingers in series by an aqueous 3 percent hydrogen peroxide solution. The impingers were kept at 0°C by immersion in an ice water bath. After finishing the sample collection, the solutions were combined and the sulfate concentration of the solution in each impinger was then determined by titration with .01 molar barium percholorate using thorin as an indicator.

Hydrogen Chloride

Hydrogen chloride was collected in an impinger train containing a standard solution of sodium hydroxide. Then the chloride was determined by titration with silver nitrate using potassium chromate as an indicator to determine the end point.

Hydrogen Fluoride

Hydrogen fluoride was sampled using dilute sodium hydroxide in the impinger absorption train. For analysis perchloric acid was added to the absorption solution and the hydrofluoric acid was separated out by steam distillation, followed by a fluoride ion determination using the S.P.A.D.N.S. dye method for a photometric procedure.

Ammonia

The gas stream from the sampler was sent through an impinger containing an alkaline solution of potassium mercuric iodide K_2HgI_4. This compound combined with NH_3 to form a yellowish-brown colloidal dispersion whose intensity of color was directly proportional to the amount of NH_3 originally present:

$$2\ K_2HgI_4 + NH_3 + 3KOH \longrightarrow NH_2Hg_2OI + KI + 2H_2O$$

Hydrogen Sulfide

During sampling the gas was bubbled through an absorption mixture of an alkaline suspension of cadmium hydroxide in the impinger. The sulfide ion was then reacted with a mixture of paraaminodimethylaniline and ferric chloride to produce methylene blue which is determined colorimetrically.

Phosphorous Pentoxide

After bubbling the gas through an acidic ammonium molybdate solution, a yellow colloidal solution of ammonium phosphomolybdate $(NH_4)_3 PO_4 \cdot 12 MoO_3$ was produced for photometric determination of the phosphate.

Water Vapor

The moisture content was determined by condensing the water vapor of the exhaust gas in a set of three jet impingers immersed in an ice water bath. The first and third impinger were empty while the second contained a scrubbing liquid (diluted sulfuric acid, H_2SO_4). The determination was carried out as a volumetric measurement.

Particulates

The high volume sampling technique was employed to measure the amount (mass) of particulates in a known gas volume per time unit. As filtering media a pre-weighed glass fiber filter with an average pore size of 0.5 micron was used (standardized by the Bay Area Air Pollution Control Districk). After finishing the particulate collection, the filter was dried and weighed again.

FLUID BED MATERIAL DESCRIPTION

The fluid bed material was washed 16-mesh "Del Monte" sand. A total weight of 483 pounds of sand was loaded into the combustor. The void fraction of the sand was 0.39. Pertinent information including typical particle distribution and typical chemical composition of this sand are summarized below:

Particle Distribution:	Chemical Composition:
0% larger than 6 mesh	SiO_2 : 86.05%
1.6% " " 16 "	Al_2O_3 : 8.17%
88.5% " " 30 "	CaO : 1.18%
8.5% " " 50 "	MgO : 0.07%
1.3% " " 100 "	K_2O : 1.96%
0.1% smaller than 100 mesh	Na_2O : 1.67%
	Fe_2O_3 : 0.22%
	TiO_2 : 0.12%

SOLID WASTE FUEL DESCRIPTION

The fuel for this test was residential solid waste collected as normal street pickup. The truck was diverted from its normal dump site to the CPC facility where the delivered refuse was shredded and air classified on July 21st. The choker bar of the Eidal shredder was set in one-half to produce "mini-fuel" with a reduced particle size to aid in feeding the model combustor. This finer shred grind setting increases the amount of inert material (fine glass and metal fragments) which is carried over with the lighter materials from the air classifier. Typically, for a fine shred, the inerts will be on the order of 15 to 20% by weight of the fuel. The moisture content after grinding was 30%. In the two day period between the grinding and combusting, the moisture content decreased by approximately 3%.

TEST CONDITIONS

The testing was initiated at approximately 8:40 A. M. on 23 July 1971. As previously described in Section III, the testing was performed using the CPC-designed Model Number 1 fluid bed combustor in the test setup shown in Figures 3-60 and 3-61. The sample collection and distribution system is shown schematically in Figure 3-62. The combustor was operated at 1400° F with the off-gases at a nominal 1600° F in the exhaust duct. The static sand height was 2 feet, and the superficial velocity was 5.2 feet per second. No techniques nor additives were added to suppress any constituent of the exhaust gas. The sampling line temperature was maintained at 360 ± 30° F throughout the test. Pertinent sampling and combustor temperature information is summarized in Table B-1.

DISCUSSION OF TEST RESULTS

The laboratory test results for the off-gases and particulates have been summarized in Tables 3-17 and 3-18 respectively. There are some differences in the description of the sampling test procedure between the Trapelo-West report and the CPC recordings. During the first run, sampling for the SO_x analysis was carried out for 20 minutes while the gas collection for the HCl, HF, and P_2O_5 determination took 30

TABLE 8-1. TEST SUMMARY SHEET

Time	Sampling type	Sampling flows			Sampling durations tot.min.	Temperatures			Comments
		Mass spec. l/min.	Lin. scrub l/min.	Part. coll. cfm		Fluid bed	Inertial		
							Tr	[illegible]	
9:40 - 10:30	–	–	–	–	–	–	–	–	Start fluidize & gas preheat cycle. Gas off/diesel on
10:30 - 10:40	Mass spec. on diesel	3.0		2.0	10				
10:40 - 10:55	–	–	–	2.0	15	1405	1465	1220	Oil off/solid waste on
10:55 - 11:08	Mass spec. on	3.0	–	–	13	–	–	–	
11:08 - 11:09	Grab bottle Orsat	–	–	–	–	1384	1460	1225	Solid waste bed cooling
11:09 - 11:16	–	–	–	3.5	7	–	–	–	Diesel on to reheat bed
11:16 - 11:23	Grab bottles hydrocarbon/NO_x	–	–	–	–	1410	1470	1225	Solid waste
11:23 - 11:46	–	–	–	3.5	22	–	–	–	Solid waste/diesel to bring bed back to nominal temp
11:46 - 12:15	SO_x sampling (sampling duration was 22 min.)	–	1.75	–	22	1420	1500	1240	Solid waste
12:15 - 12:25	Reheat bed	–	–	3.5	10	–	–	–	Solid waste/diesel to reheat bed
12:25 - 12:56	HCl, HF, P_2O_5	–	2.0	–	30	1440	1570	1280	Solid waste
12:56 - 1:04	–	–	–	3.5	8	–	–	–	
1:04 - 1:10	Mass spec.	3.0	–	–	6	1440	1570	1280	
1:10 - 1:13	–	–	–	4.5	3	–	–	–	
1:14 - 1:29	[illegible]	–	2.0	–	15	1400	1570	1250	
1:29 - 1:35	–	–	–	4.0	6	–	–	–	

Table B-1 (continued). TEST SUMMARY SHEET

Time	Sampling type	Sampling flows: Mass spec. l/min.	Sampling flows: Liq. scrub l/min.	Sampling flows: Part. coll. cfm	Sampling duration tot.min.	Temperatures: Fluid, °F	Temperatures: Inertial °C	Temperatures: Inertial °F	Comments
1:36 – 1:51	H_2S	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
1:52 – 1:55	–	–	–	4.0	3	–	–	–	
1:56 – 2:11	NO/NO_2	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
2:11 – 2:14	–	–	–	5.0	3	–	–	–	
2:14 – 2:25	Grab bottles (Orsat, hydrocarbons, NO_x)	–	–	–	–	[illegible]	[illegible]	[illegible]	
2:25 – 2:40	SO_x	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
2:40 – 2:45	–	–	–	5.0	5	–	–	–	
2:45 – 3:00	HF/HCl, P_2O_5	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
3:00 – 3:05	–	–	–	5.0	5	–	–	–	
3:05 – 3:13 3:16 – 3:23	NH_3/H_2O	–	2.0	–	15	[illegible]	[illegible]	[illegible]	Interrupted sampling due to feeder valve jam, put off on between 3:13 – 3:16
3:24 – 3:39	H_2S	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
3:39 – 3:47	–	–	–	5.0	8	–	–	–	
3:47 – 4:02	NO/NO_2	–	2.0	–	15	[illegible]	[illegible]	[illegible]	
4:02 – 4:[illegible]	–	–	–	–	–	–	–	–	Changed over to [illegible] high velocity particle sampler
4:[illegible] – 4:45	–	–	–	[illegible]	15	[illegible]	[illegible]	[illegible]	

minutes (see Table B-1). As the Trapelu West calculations were based on the assumption of a 15 minute collection time the results regarding these four gases had to be recalculated. (See Table 3-17.)

GAS ANALYSES

The analytical results revealed six major constituents for the combustor off-gas, namely N_2, O_2, CO_2, Hydrocarbons, H_2O and CO. All other constituents appeared in such small quantities that their concentration can better be expressed in parts per million (ppm) units rather than in percentages.

The amounts of N_2, O_2, CO_2, and H_2 are typical for combustion exhaust gas while the concentrations of unburned hydrocarbons and CO are unusually high and low, respectively.

The results of the Orsat analyzer had to be corrected due to the fact that the determination of N_2 (as customary) was done by totaling the CO_2, CO and O_2 percentages and subtracting the same from 100 neglecting the presence of the other major constituents. The correction coefficient was determined for both sets of Orsat analyzer results as

$$C_1 = \frac{91.5}{100} = .915 \text{ and } C_2 = \frac{95.6}{100} = .956\text{, respectively.}$$

The corrected gas composition is shown in the right side column of Table 3-17.

The differences in gas composition between the first and second sampling sequences can be explained not only by the fact of a varying garbage feed composition due to the heterogenous character of municipal refuse but also by deviations in the test procedure during the first sampling sequence.

As can be seen in the test summary sheet (Table 8-1) some operational difficulties were encountered during the first two hours of the test. In order to maintain the bed temperature at 1400° F the solid waste feeding was interrupted three times by reheating cycles with diesel oil. Past testing has periodically shown that the model fluid bed combustor retains partially decomposed diesel oil in the sand next to the distributor plate. The samples collected after each reheat cycle are suspected of being contaminated by the oil products that persisted in the combustor during the start of each solid waste feed period. This is especially true for gases like hydrocarbons whose concentration dropped from initially 5.9 percent to 2.4 percent in the second run where no reheat cycles were used. The same explanation can be given for the concentration variations of sulfur oxides and phosphorus pentoxide which are closely related to the presence of hydrocarbons.

Therefore, we can assume that the analyzed gas samples collected after 1:10 P. M. represent more accurate results. Accordingly, the last five test samples of the first run taken after 1:10 P. M. (NH_3, H_2O, H_2S, NO, NO_2) show a much better correlation with the corresponding results of the second test run.

The discrepancy between the NO_x analyses and the results of a separate NO and NO_2 determination are probably due to a different sampling technique. NO and NO_2 were determined separately on-line while the gas sample for the NO_x analysis was collected in an evacuated glass flask and analyzed later in the Trapelo laboratories. It is likely that some of the NO_x gases reacted with the water vapor in the flask to form nitrous or nitric acid and thus became undetectable by a later application of the Saltzman method.

The NO_x concentration appears to be rather low compared with data from other combustion processes. To confirm these results the Trapelo West Laboratory rechecked both the analytical procedure and the calculations.

The measured concentrations of SO_x and HCl appear to correlate well with studies about the composition of municipal refuse. According to some data from Battelle and Bureau of Solid Waste Management typical municipal garbage contains HCl in a concentration range of 80 to 200 ppm and SO_2 always in a significantly small amount. The concentrations of HF and H_2S were expected to be rather low since municipal refuse contains only traces of these compounds. In addition, H_2S is thermodynamically unstable at higher temperatures, therefore, its presence in the hot exhaust gas is very unlikely. As the analytical method to determine HF is known to be rather specific and sensitive, the results can be considered as a reliable indication that only traces of HF are present.

The combustible gases hydrogen and methane could not be detected in the gas samples by the employed gas chromatograph whose sensitivity is restricted to 1 ppm. This result is somewhat surprising, at least for CH_4 since the exhaust gas consisted of 2.4 - 5.9 percent hydrocarbons which normally are accompanied by small amounts of methane.

the difference in the results of the P_2O_5 determination has already been discussed previously in connection with the heating problems during the first test run. It means that a P_2O_5 concentration in the garbage feed flue gas of 0.1 ppm is more likely than higher concentrations caused by remaining diesel oil fractions in the combustor bed.

FLYASH ANALYSES

The flyash collected at the exit of the inertial separator residue collection tank (the secondary particulate collection point) was analyzed by the Trapelo West Laboratory as well as by another outside laboratory, the Metallurgical Laboratories Incorporated in San Francisco.

Trapelo West determined the anions Cl^-, F^-, P_2O_5, and SO_4^{-2} and also ran emission spectroscopic analyses for the primary and secondary particulate collection. Metallurgical Laboratories Incorporated determined the concentration of the major constituents of the flyash from the secondary particulate collection point by wet chemical methods while the minor constituents were derived from an emission spectrum. The method used by the Metallurgical Laboratories for determining the anions employed a fusion of the flyash with Na_2CO_3. The solution of the fused salts in water could be used for determining the anions as follows:

P_2O_5	by the ammonium phosphomolybdate method
SO_4	by standard titration with $BaCl_2$

Cl by standard titration with $AgNO_3$

F by steam distillation with $HClO_4$, photometrical determination of the fluorine - Zr - alizarin lake

The results of the flyash analyses are summarized in Table 3-18. It must be noted that the percentages listed are converted values for metal oxides.

The results obtained from the different flyash samples, especially the two secondary particle collection samples analyzed by two different laboratories, show some discrepancies for the major components. Since both laboratories were sent parts from the same sample these differences must primarily be associated with the low emission spectrograph accuracy for the major components. The wet chemistry approach used by the Metallurgical Laboratories Incorporated for the high concentration components are expected to be the more accurate levels.

No attempt was made to sample isokinetically for measuring particulate concentrations because the model combustor test set-up did not use staged particle separation equipment which was under devopment for the full scale combustor (see Appendix C) system. In accordance with the test plan, the particulate chemical concentrations are prorated for the full scale gas cleaning system to the particulate loading goal of 0.001 grains per cubic foot. This particle loading can be converted into parts per million by the following relationship:

0.001 grain/cft = 1.9 ppm by weight

Expected concentrations of flyash constituents in the cleaned gas entering the turbine can be determined by multiplying 1.9 ppm by the weight fraction of the respective constituents.

RECOMMENDATION FOR THE TURBINE BLADE MATERIAL TEST

From the results of the analyses of the combustor exhaust gas and flyash the constituents cited below were recommended for use in the turbine blade material testing. The constituents listed are based on the test results summarized in Tables 3-17 and 3-18. All constituents with concentrations below 0.05 ppm were considered to be negligible.

Gases	Particulates
N_2 : 75.0%	SiO_2 : 0.8 ppm
O_2 : 14.8%	Al_2O_3 : 0.5 ppm
CO_2 : 5.2%	Na_2O : 0.1 ppm
CO : 0.2%	K_2O : 0.06 ppm
H_2O : 2.3%	CaO : 0.2 ppm
HC : 2.4%	MgO : 0.06 ppm
SO_2 : 10 ppm	Fe_2O_3 : 0.1 ppm
HCl : 90 ppm	
P_2O_5 : 0.1 ppm	

Testing was conducted by the Westinghouse Research Laboratories, Combustion Systems Research Group under EPA contract 68-03-0045.[4] As previously mentioned in Section III, the test results showed no attack other than oxidation. Oxide scales were left intact even though the deposit spalled, and no localized attack was found other than normal penetration of oxide at grain boundaries in spite of the presence of chlorine, sulfur, and alkali metals in the test environment. Conservative extrapolation of the data indicated that a machine life in excess of 10,000 hours should be obtainable.

APPENDIX C

GAS COMPOSITION AND PARTICLE ANALYSES OF EXHAUST GAS FROM THE FULL SCALE VERTICAL COMBUSTOR

INTRODUCTION

This appendix describes the equipment used for the full scale vertical combustor exhaust gas composition analyses, and discusses the techniques employed in the determination of the exhaust gas stream particle loading and size distribution. Carbon monoxide, carbon dioxide, hydrogen chloride, sulfur dioxide, hydrocarbons, oxygen and oxides of nitrogen were the exhaust gas compounds selected for gas composition and particle analyses. Results of these analyses are presented in Section V.

GAS COMPOSITION ANALYSIS DESCRIPTION

The gas analysis systems (Figures C-1 and C-2) consist of a sampling and distribution system, analytic instrumentation and analog data recorders integrated into a mobile rack mounted complex. The sampling system provides particle removal, gas cooling, drying, temperature and flow control. Also incorporated into this system, where interference gases are concerned, were methods for reducing the component of interest. In addition, a method of zero setting has been included within the sampling distribution manifold.

from the sampling point in the exhaust gas line, the gas sample is routed through a particle filter located at the sampling probe outlet. The particle filter is rated at 5 microns and can function at temperatures above 1500° F. After passing through the filter, the gas sample is cooled by radiation losses of the sample line to the heat exchanger. The heat exchanger further cools the sample to about 50° F and removes water to this temperature saturation point. A probe removes cooled sample gas from the heat exchanger after which the gas is heated and controlled to a temperature of 100° F. It is then pumped and regulated to the distribution manifold from which the sample flow rates to the analysis instruments are kept within 10 percent or better with individual needle valve controllers.

The rack mounted analysis instruments include: two infrared analyzers (Beckman Model 315A), a flame ionization detector (Beckman Model 400), two electrochemical reaction cells (Theta Sensor Models LF-800AS and LS-800AN), and one polarographic analyzer (Beckman Model 715).

Carbon Monoxide and Carbon Dioxide

These two gases are measured with Beckman Infrared Analyzers, Model 315A(S) (Short-Pathlength). Each analyzer automatically and continuously determines the concentration of the particular component of interest in the gas mixture. The analysis is based on a differential measurement of the absorption of infrared energy.

To measure the differential absorption of infrared energy, the instrument uses a double-beam optical system contained in the analyzer section. Two infrared sources are used, one for the sample energy-beam, the other for reference energy-beam. The beams are blocked simultaneously 9.25 times per second by a chopper - a two-segmented blade rotating at 4-5/8 revolutions per second. In the unblocked condition, each beam passes through the associated cell and into the detector.

The sample cell is a flowthrough tube that receives a continuous stream of sample. The reference cell is a sealed tube filled with a reference gas, which is selected for minimal absorption of infrared energy of those wave lengths absorbed by the sample component of interest.

The detector consists of two sealed compartments separated by a flexible metal diaphragm. Each compartment has an infrared-transmitting window to permit entry of the corresponding energy beam. Both chambers are filled, to the same sub-atmospheric pressure, with the vapor of the component of interest (CO or CO_2). Use of this substance as the gas charge in the detector causes the instrument to respond only to that portion of net difference in energy due to the presence of the measured component.

During operation, the presence of the infrared-absorbing component of interest in the sample stream causes a difference in energy levels between the sample and reference sides of the system. This differential energy increment undergoes the following sequence of transformations:

1. Radiant energy - In the sample cell, part of the original energy of the sample beam is absorbed by the component of interest. In the reference cell, however, absorption of energy from the reference beam is negligible.

2. Temperature - Inside the detector, each beam heats the gas in the corresponding chamber. Gas in the reference chamber is heated more, however, since energy of the reference beam is greater.

3. Pressure - Higher temperature of gas in the reference chamber raises pressure of this compartment above that of the sample chamber.

4. Mechanical Energy - Gas pressure in reference chamber distends diaphragm toward sample chamber. The energy increment is thus expended in flexing diaphragm.

5. Capacitance - The diaphragm and an adjacent stationary metal button constitute a two-plate variable capacitor. Distention of the diaphragm away from the button decreases the capacitance.

When the chopper blocks the beams, pressures in the two chambers equalize and the diaphragm returns to its undistended condition. As the chopper alternately blocks and unblocks the beams, therefore, the diaphragm pulses, thus changing detector capacitance cyclically. The detector is part of an amplitude modulation circuit that impresses the 9.25 Hz information signal on a 10 MHz carrier wave provided by a crystal-controlled radio frequency oscillator. Additional electronic circuitry in the oscillator unit demodulates and filters the resultant signal, yielding a 9.25 Hz signal. The 9.25 Hz signal is routed to one amplifier/control section for amplification and phase inversion, then back into the analyzer section for synchronous rectification. The resulting fullwave-rectified signal is returned to the amplifier/control section for filtering and additional conditioning, as required, to drive the meter and recorder.

The meter reading is a function of the concentration of the component of interest in the sample stream. When the instrument is put into operation, it is adjusted so that a reading of zero corresponds to a concentration of 0 percent of the component of interest, while a fullscale reading corresponds to the highest concentration in the operating range covered.

Hydrocarbons

The hydrocarbons in the exhaust gas are detected with a Beckman Model 400 hydrocarbon analyzer. This analyzer utilizes the flame method of detection to determine the concentration of hydrocarbons present in a gas stream or ambient air. The flame formed when hydrogen burns in air contains a negligible number of ions. Introduction of mere traces of hydrocarbons into the flame results in a complex of ionization, producing a large number of ions. A polarizing voltage applied between the burner jet and the collector produces an electrostatic field in the vicinity of the flame. The electrostatic field results in an ion migration whereby the positivu ions are attracted to the collector and the negative ions to the burner jet. Thus, a small ionization current is established between the two electrodes. This small current is directly proportional to the hydrocarbon concentration in the flame and is measured by an electrometer amplifier circuit.

The amplifier circuit provides the driving voltage for an indicating meter and recorder. The magnitude of the electrometer amplifier signal is indicative of the number of carbon atoms passing through the flame.

The "carbon counting" characteristic of the detector is proportional to both the sample flow rate and the nature of the sample. For example, a flow of 10 cc/minute of a given sample provides a signal approximately twice as great as that produced by a flow of 5 cc/minute of the same sample. Also, a given volume concentration of a typical C_6 hydrocarbon produces a signal twice as great as an equal volume concentration of a C_3 hydrocarbon, or six times as great as an equal volume concentration of a single carbon (CH_4) hydrocarbon. Instrument characteristics, such as sensitivity, are thus typically reported in terms of CH_4 (methane) equivalent.

Oxygen

The oxygen in the exhaust gas is measured with a Beckman Model 715 process oxygen monitor. The monitor consists of two basic modules: an amperometric oxygen sensor and an amplifier unit. The sensor detects the partial pressure of oxygen present; the amplifier measures the magnitude of the sensor signal, which may then be read directly on the meter or used to drive a 10-millivolt recorder.

The amperometric oxygen sensor contains a gold cathode and silver anode. The two electrodes are separately mounted within a PVC body, and are electrically connected by a potassium chloride electrolyte. A constant potential is impressed across the two electrodes. A gas-permeable teflon membrane separates the electrodes from the process sample, and fits firmly against the gold cathode. Oxygen from the sample diffuses through the membrane and is reduced at the gold cathode. The resultant electrical current flow between the anode and cathode is proportional to the partial pressure of oxygen in the sample.

The amplifier contains a meter, controls, and a solid-state, drift-free feedback amplifier which measures the current level generated by the sensor. The meter has two scales that correspond to the two ranges provided by the range switch, and a third scale for dissolved oxygen, percent saturation, or partial pressure measurements. Air calibration is made on the 0 to 25 percent scale by setting the meter pointer to 20.9 percent via the calibrate control. The calibrate control is equipped with a locking device to prevent inadvertent changes of the calibration setting.

Sulfur Dioxide and Oxides of Nitrogen

These two gases are monitored with Theta Sensor Model LS-800 analyzers. One analyzer (Model LS-800AS) measures both NO_x and SO_2. Its response is identical to NO_x and SO_2, therefore allowing for direct subtraction of the SO_2 measurement in order to determine NO_x. Each unit is a single-channel instrument designed to provide quantitative measurement of the SO_2 or SO_2 and NO_x as found in the stack emissions.

The principle of operation utilizes a combination of semi-permeable membrane and selective redox reactions within the completely sealed transducer. The electrical signal from the transducer is directly proportional to the concentration of the pollutant in the gas environment being monitored. The response is linear over the 0 to 5000 ppm range covered. The transducer is a totally enclosed, sealed plug-in unit. The instrument is equipped with a set of three range selector switches (L, M, H) allowing the selection of a desired sensitivity for full scale meter readings of 500, 1500, or 5000 ppm, respectively.

Hydrogen Chloride

Hydrogen chloride in the exhaust gas is monitored by use of the Volhard titration method. Discrete samples are taken at 2 to 5 hour time intervals to determine the average HCl concentrations present in the exhaust. A volume of the exhaust gas was first bubbled through a solution of sodium hydroxide. The liquid was then analyzed in the laboratory for the concentration of sodium chloride. As previously mentioned, an attempt to procure an on-line instrument for HCl measurement using a gas chromatograph was abandoned when the instrument subcontractors determined that it was beyond the state-of-the-art.

OFF-LINE DETERMINATION OF GAS STREAM PARTICLE LOADING AND SIZE DETERMINATION

The remaining pages in this appendix describe a technique for off-line determination of the loading and size distribution of particles in a gas stream and provide a general procedure with typical results.

Particle analysis has historically resided somewhere between a pure science and a black art. There are three reasons for the problems involved in particle analysis. First, it involves probability. It deals with the representative sample as opposed to an exact measurement. The particle counts determined for one sample are not necessarily identical to the particle counts determined for a different sample taken from the same system under seemingly identical conditions. Similarly, if a sample is divided into two equal parts, the analysis of each part will probably provide somewhat different results.

The second problem encountered in particle analysis is that it involves sizes and counting of parts that generally cannot be seen with the unaided eye. This together with the need for relatively large sample counts to increase the confidence level in the results makes optical count methods tedious and prone to error.

The third problem involved with particle distribution analysis is the susceptibility to the introduction of errors in the results when great care is not used in sampling or analyzing the data. The results can be drastically altered by particles from the atmosphere, particles introduced by the act of connecting and disconnecting lines to the sampling system, particles lost or extra particles introduced by sampling at non-isokinetic conditions, particles introduced by the laboratory equipment used in the analysis, particle loading variations resulting from leaks in the sampling system, etc. While such problems are subtle, they can have a devastating influence on the results.

It is for these reasons that it is imperative to have a proven procedure to determine particle size distribution and to have the personnel involved in the sampling and analysis sufficiently familiar with the equipment, technique, and philosophy to recognize when problems are occurring.

Techniques for Determination of Particle Size Distribution

The determination of particle size distribution in a gas stream involves three operations: system sampling, sample analysis, and data reduction.

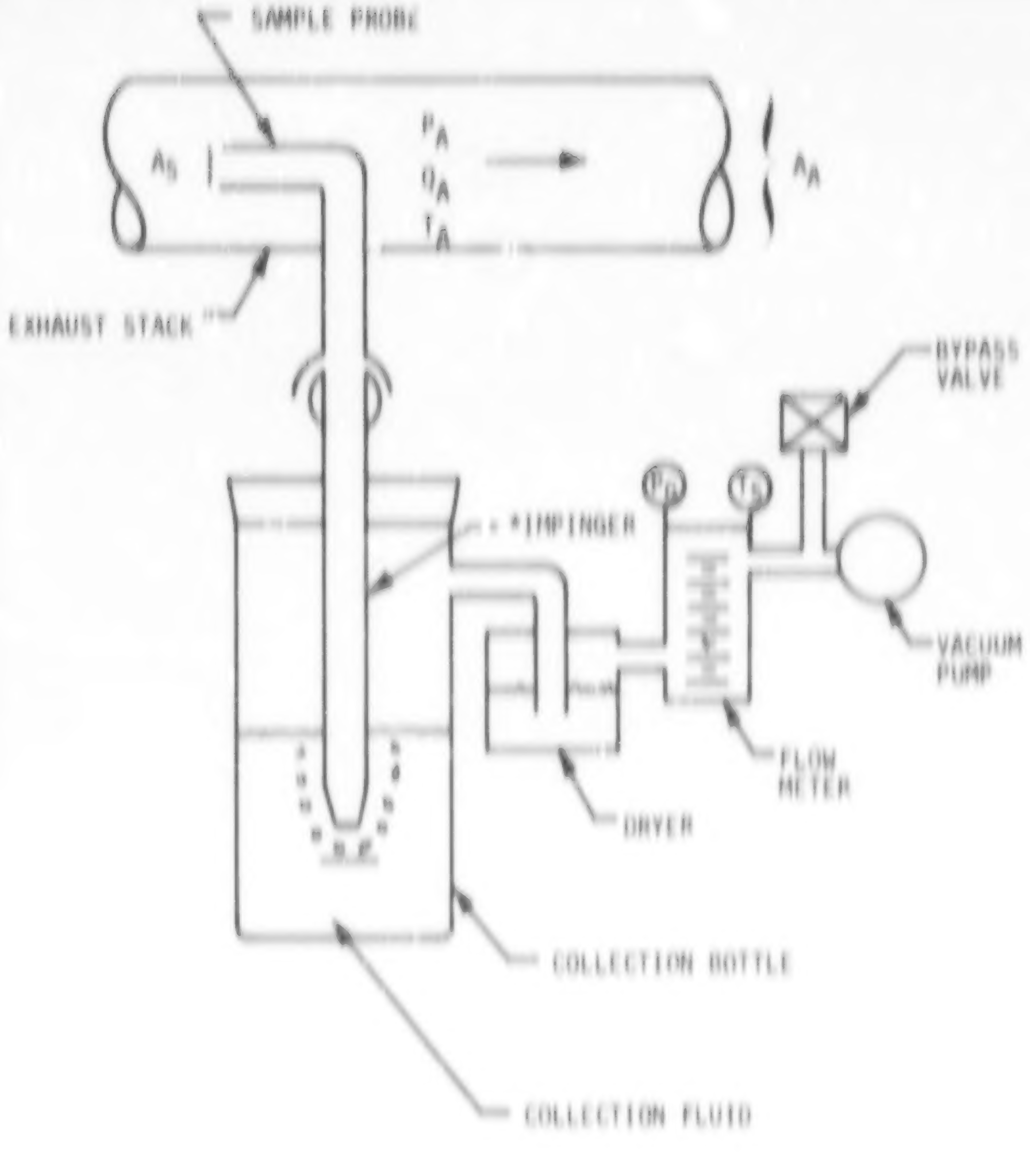
The general approach to be followed for each of these operations is discussed below.

Isokinetic Sampling.

The basic technique for obtaining a sample for later analysis is to pass a representative sample of the particle laden gas through a liquid, collect the particles in the liquid and allow the gas to escape to the atmosphere. A schematic of the sampling system is illustrated in Figure 8-14.

The main consideration is to insure that the sample is a representative sample. To accomplish this, the sample must be collected isokinetically. In other words, the velocity of the gas entering the sampling system must be equal to the velocity of the gas that bypasses the sample tube. If the velocity of the gas entering the sampling system is greater than the velocity of the surrounding gas, the inertia of some large particles would prevent them from following flow streams and entering the sampling tube (Figure 8-15a). The sample will therefore tend to be light in the number of large particles counted. Similarly, if the sample velocity is less than the velocity of the surrounding gas, the inertia of some heavier particles will cause them to continue into the sample tube rather than follow the flow stream around it, thus tending to increase the number of large particles in the sample (Figure 8-15b). Assuming that the gas follows the perfect gas law, the indicated volume flow rate for the system shown should be:

$$Q_s = \frac{A_s\ T_s\ P_a}{A_a\ T_a\ P_s}\ Q_a \qquad (1)$$


SAMPLE PROBE
A_S
P_A
Q_A
T_A
A_A
EXHAUST STACK
BYPASS VALVE
P_M
T_M
*IMPINGER
VACUUM PUMP
FLOW METER
DRYER
COLLECTION BOTTLE
COLLECTION FLUID

* NOTE: Impingers are designed for a certain range of flow rates and should be used only within that range.

Figure B-14 Sampling System Schematic

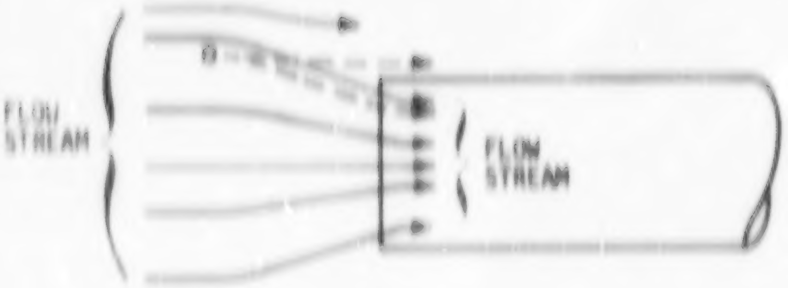

FLOW
STREAM
FLOW
STREAM

Figure 2A Hyper-Isokinetic Sampling

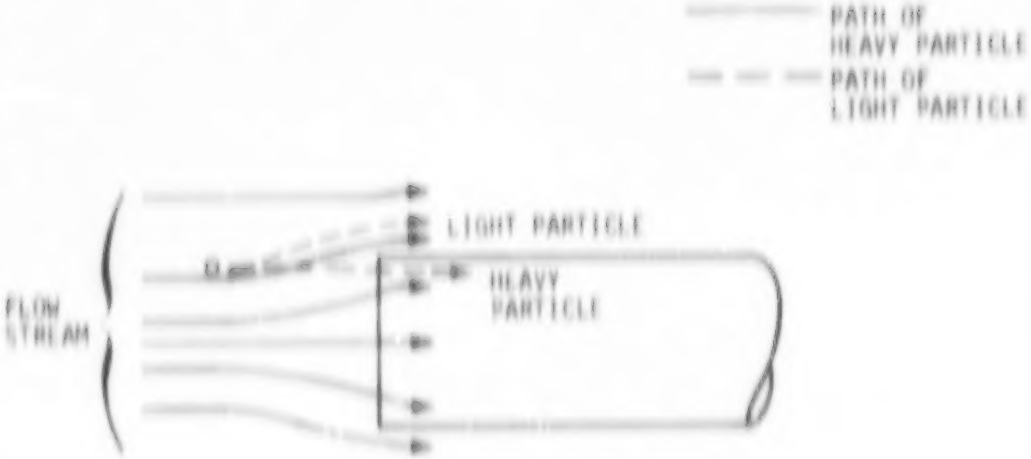

PATH OF
HEAVY PARTICLE
PATH OF
LIGHT PARTICLE
LIGHT PARTICLE
HEAVY
PARTICLE
FLOW
STREAM

Figure 8-15 Non-Isokinetic Sampling

where: A_s = sample tube entrance area

A_a = stack area

T_s = sample absolute temperature in the flowmeter

T_a = stack absolute temperature

P_s = sample absolute pressure in the flowmeter

P_a = stack absolute pressure

Q_s = volumetric flow rate of sample

Q_a = stack volumetric flow rate

Assuming standard temperatures and pressures

$$Q_s = \frac{A_s}{A_a} \frac{530}{(T_a' + 460)} \frac{(P_a' + 14.7)}{14.7} Q_a \qquad (2)$$

where: T_a' = stack temperature in degrees Fahrenheit

P_a' = stack gas pressure in psig

By maintaining the established flow rates through the impinger for a specific period of time, the sample will represent a known quantity of gas. For example, a flow rate of one cubic foot per minute measured at the flow meter and maintained for 5 minutes will result in a sample which contains all the particles from 5 cubic feet of gas at the temperature and pressure of the gas in the flow meter (normally close to standard conditions). However, this assumes no errors in sampling. If a leak exists in the sampling train or the sample tube, and the sample tube pressure is below atmospheric pressure, the measured flow rate will represent the sample flow plus a leakage flow. The collected sample will therefore represent something less than the 5 cubic feet previously computed. If the sample system pressure is above atmospheric pressure, the leak will be outwards, the particles will probably follow the main stream rather than the leakage flow path and the collected sample will be representative of an unknown volume somewhat in excess of the 5 cubic feet calculated. Either case will result in an error in loading and probably in the distribution.

Another area of potential error is the introduction of particles other than those entering the sampling tubes. These can be introduced by the act of filling the sampling bottle with collection fluid, connecting or disconnecting the sampling bottles or handling of the particle laden sample after collection, or before or during analysis.

On the other hand, particles entering the sample tube can leave the sample air stream and be caught in voids in the sampling train thereby resulting in a lower than actual loading. This can occur if condensation takes place within the sampling train before the sample enters the impinger, or if large temperature changes take place between the sample point and the collection bottle. Such temperature changes cause thermal gradients across the flow stream which in turn cause cross stream flow. This cross stream flow leads to the deposition of particles on the sampling train wall.

Particle Analysis:

An automatic particle counter is used to determine the particle quantity and distribution in the sample. The sampling configuration is illustrated in Figure 8-16. A measured quantity of particle laden fluid is drawn through an orifice of known size. The fluid is an electrolyte,

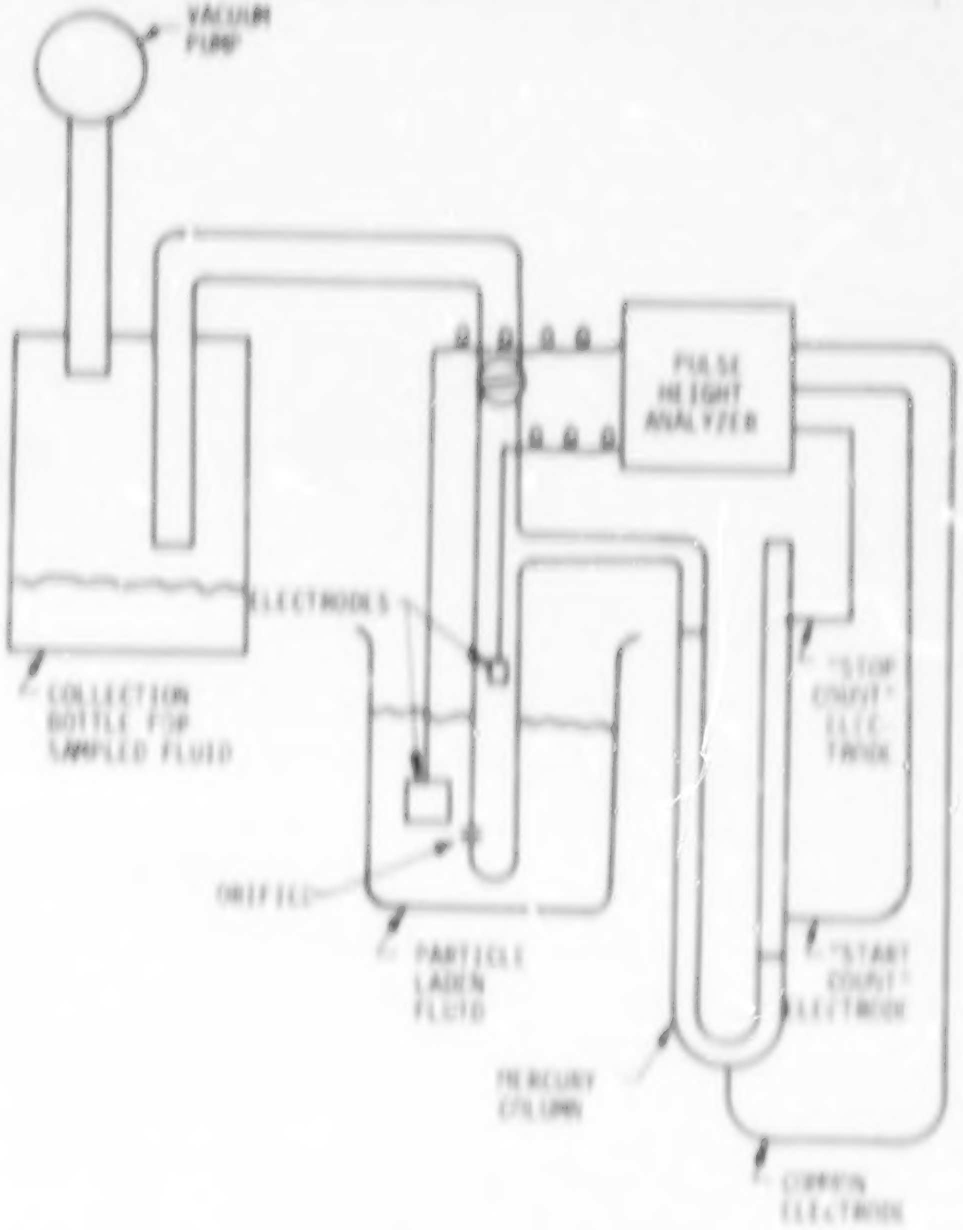

VACUUM PUMP
PULSE HEIGHT ANALYZER
ELECTRODES
COLLECTION BOTTLE FOR SAMPLED FLUID
"STOP COUNT" ELECTRODE
ORIFICE
PARTICLE LADEN FLUID
"START COUNT" ELECTRODE
MERCURY COLUMN
COMMON ELECTRODE

Figure 8-16 Particle Analyzer System

thus allowing for a current to be passed through the orifice which is the major resistance to current. Particles passing through the orifice act to reduce the cross sectional area available to current flow, thereby increasing the current path resistance. By measuring the change in resistance at the orifice, it is possible to determine the size of particles going through. Within the working band of the orifice, the change in measured resistance is proportional to the current, to the signal amplification and to the volume (or diameter^3) of the particle. The unit is usually set up to measure the number of times the change in resistance exceeds a set value during a single draw of sample through the orifice. The unit used to measure the change in resistance is a pulse height analyzer. A standard pulse counter counts the output of the analyzer. Since the resistance limit threshold for the pulse height analyzer corresponds to a particle size, the unit will essentially count the number of particles that exceed a selected size. By starting and stopping the counter using a mercury column switch network which draws in a specified quantity of particle laden fluid, it is possible to count the number of particles in a known quantity of fluid that exceeded a pre-selected size. The number of particles that exceeded the pre-selected size in a cubic foot of gas can then be determined by:

$$N/ft^3 = \frac{(V_s)}{(V_g)} \frac{(N_a)}{(V_a)} \qquad (1)$$

where: V_a = volume drawn through analyzer (ml)

V_s = volume of sample (ml)

V_g = volume of gas represented by sample (ft^3)

N_a = analyzer count

Using different resistance thresholds, correspond to different particle sizes, for a number of measurements, it is possible to obtain a distribution for the particles collected from the sample gas stream.

As with all particle counting systems, errors can be encountered with this sizing technique. Any change that can cause an apparent change in the measured resistance can cause errors in counting. Electrical fields such as those emitted by spark plugs can generate currents in the sample, thus causing high particle counts. Mechanical vibrations in the equipment can also cause apparent resistance changes between the probes. In some cases, it has been observed that mechanical vibrations can mask small particles going through the orifices, thereby causing a reduction in the small particle counts. Another problem area is in the orifice. Particles on occasion tend to partially block the orifice. Any particles going through the orifice will then appear larger (greater change in resistance) than they actually are.

The only good technique to avoid erroneous readings due to these conditions is to be familiar with the characteristic signal from the sensor (displayed on an oscillosope). When the signal is apparently bad, the operator should check the orifice for plugging and check the area for excessive electrical or mechanical noise.

Another area that can cause erroneous readings is to attempt to use the instrument outside of its designed range. Counting too many particles (a heavily contaminated sample) will cause coincidence problems where a number of small particles go through the orifice concurrently and are therefore measured as a single large particle. Attempting to count too few particles is equally bad because background counts can exaggerate the data. Also, attempting to count exceedingly small particles with respect to the orifice size can lead to a high count due to noise.

Data Reduction-

Reducing the data into a form suitable for evaluation of a system involves a number of steps, especially if the data is to be used for evaluation of particle separators or other devices for which is it desired to compare two readings. The reduction of particle analysis data can be greatly improved by familiarity with characteristic trends of particulate distribution. Such knowledge makes it possible for the data evaluator to detect and compensate for sampling and analytical errors, and equipment deficiencies.

Particle distribution for a number of particle generators including a fluidized bed generated exhaust tend to follow a straight line when plotted on log-log paper (a special graph paper which is not available commercially but which can be generated via a computer program and peripheral plotter). The analytical data is initially normalized to a unit gas volume and then plotted on the log-log paper. The plot is then examined for deviations from a smooth curve and corrections made as required. If loading and distribution for single samples only are required, the resulting curve is used directly for distribution determination. This involves dividing the curve into a number of segments, each representing a range of particle sizes, computation of the number of particles in each increment by simple subtraction, computation of the total volume represented by the particles in each increment using a mean diameter and finally, computation of the equivalent weight of particles in each increment using a standard density. From these last figures, a plot can be generated which displays the total weight of particles exceeding the micron size indicated by the graph ordinate. The effort required for this complete data reduction process can, of course, be greatly reduced by having available and using appropriate computer programs.

If two distributions are to be compared, such as for determination of particle collection efficiency in a separator, it is necessary to further condition the data from the analysis prior to loading evaluation. First, the ratio of the two loading curves is calculated and plotted (plotting is usually done on a log-log graph). This plot presents the separator efficiency versus particle size, efficiency being the ability of the separator to remove all particles of the noted size. As with the initial distribution curves, the efficiency curve should be smooth and the efficiency should continuously increase as the particle size increases. Following curve smoothing and conditions by the data evaluator, the efficiency curve and the separator input loding curve are used to generate a new output loading curve. This is done since the output sample is usually prone to background noise and introduction of errors through contamination of the sample. (In some cases, background noise has caused an apparent decreasing and even a negative efficiency in a separator output. This can occur when the ratio of particle counts over the size range of interest is in excess of 1000:1). Following this data conditioning, the two curves are reduced for loading as for the single curve case.

General Procedures and Typical Results

The general procedures to be followed for sampling, analysis and data reduction are presented below. Sample worksheets are frequently used to provide typical results.

Sampling Procedure-

The volumetric flow rate of gas in the exhaust stack or sampling point must initially be determined. This is normally achieved using a calibrated orifice with known coefficients and correcting for the temperature and pressure within the stack. If the velocity is high (the usual case in fluidized combustion systems) the particles will probably be evenly distributed across the stack and the velocity profile will be relatively flat. If not, corrections should be made for the velocity profile and samples should be taken at a number of points in the stack to insure that the sample is representative of the gas stream.

A sampling tube should then be installed in the stack. The tube should be sized to allow for a flow compatible with the sampling system (note that impingers are designed for specific ranges of flows). The collection bottle should be filled with an appropriate amount of collection fluid and the impinger installed. The impinger should then be connected to the sampling train and checked for leaks by turning on the vacuum pump with the impinger inlet blocked. Any flow in the flow meter indicates a leak.

The sampling train should be connected as close as possible to the sample point at the start time and the calculated sample flow rate set. Temperature and pressure within the flow meter should be recorded for later flow rate verification. Also, any abnormal condition encountered during sampling should be noted.

Following sample collection, the impinger should be withdrawn from the collection bottle and any particles deposited on the inlet washed into the bottle using the proper solution. Final sample volume should be recorded in order to allow conversion of the data to a unit gas volume. (See sample data sheets).

On occasion, a background sample should be taken. This involves placing a filter on the end of the sampling probe and taking a sample as though it were a standard exhaust emission sample. It is important to follow the same procedure used for standard sampling when taking the background sample. Sometimes, an investigator will use greater care with the background sampling and analysis than is used for exhaust gas sampling and analysis. This makes the background data "look good" but of little use when using background results for stack analysis correction.

Data Analysis:

The particle counter should first be calibrated using the orifice selected for sample analysis. A typical data sheet is shown in Figure B-17. The main objective is to determine instrument settings that correspond to a known particle size. Usually a pollen is used for calibration and the breakpoint (point at which half the particles are larger than the

Initial Calibration Date 6/3/76

Orifice 70 µ

Resistance 20,000

Calibration particles 12 - 13 µ

Settings

Trim 0.25

1/A 16

1/T 1/4

NOTE: Establish settings such that readings at a t_1 setting of 10 are twice the readings that occur with a t_1 setting of 56. (t_u at max.)

Background at t_1 = 10 2

1

3

Readings at t_1 = 10

1. 1285
2. 1195
3. 1253
4. 1310
5. 1270

Sum 6313

1/2 (average) = $\frac{1}{10}$ 6313

631 = half count

Readings at t_1 = 56 (set to obtain above half count) (trial and error)

1. 622
2. 644
3. 638
4. 630
5. 628

Sum 3162

Check = $\frac{\text{Sum}}{5}$ = 632

Calculate K' (Based on D^3 rather than V)

$$K' = \frac{D^3}{T \times A \times t_1} \quad D \text{ in } \mu$$

$$= \frac{(12.5^3)}{1/4 \times 16 \times 56} = 10.0$$

Figure B-17 Initial Calibration Data Sheet threshold and half the particles smaller than the threshold) is determined by trial and error. Once the settings for the known particles are established, settings for other particle sizes can be calculated.

It has been found from past experience with the counter that settings should be established such that the operator has to adjust only the amplifier gain. The adjustment for this setting can be varied from 1/8 to 64 in 10 steps, resulting in a possible threshold variation corresponding to an 8 to 1 particle diameter range. (It should be noted that the instrument settings are for the inverse of the amplifier gain and the inverse of the orifice channel.). This range is usually sufficient for particle loading and distribution. Equivalent particle diameter for each setting of the amplifier gain control can be calculated from:

$$D = \sqrt[3]{(K')\ (1/I)\ (1/A)\ t_l} \qquad (4)$$

where: K' = the calibration factor previously calculated

1/I = the current control setting

1/A = the amplifier control setting

t_l = the lower threshold setting

D = the equivalent particle size in microns

The upper threshold (t_u) is adjusted to the maximum setting for all standard counter operations and the trim is set at the value used during calibration.

By selecting appropriate single fixed values for $1/I$ and t_i, all diameters of normal interest can be covered by the available amplifier control settings.

In recalibrating the unit, it has been found best to set up the original calibration settings and then adjust the trim knob to obtain the appropriate break point of the calibration sample with these settings. The data analysis sheets can then be updated to the latest calibration point by using the latest trim setting and using the originally selected values for the other settings. (See Figure 8-18).

After calibration, the system is ready for particle analysis. Some of the specific procedures to be followed when obtaining distribution data are:

1. The counter should be warmed up for one hour prior to analyzing any samples.
2. Samples should be analyzed the same day that they are collected.
3. If it is necessary to filter the sample in order to avoid plugging, use a mesh in the same size range as the sampling orifice. Filter the sample prior to any dilution and then use the dilution fluid to wash the particles through the mesh.
4. All samples should be within 50° F of each other when analyzed.
5. When splitting (or reducing) the sample size, pour sample between two beakers a number of time, reducing the amount transferred each time until the desired volume is obtained in one of

Date 6/9/88

Orifice 70 µ

Resistance 1/5 Null

Calibration particles 12 : 11

Original settings

NOTE: Establish settings such that readings at a t_l setting of 10 are twice the readings that occur with a t_l setting of 50. (t_u at max.)

Trim 4.25

1/A 16

1/I 1/4

t_l = 54 at half count

Background at t_l = 10 2
1
3

Readings at t_l = 10

1. 1072
2. 1128
3. 1148
4. 1178
5. 1167

Sum 5694

1/2 (average) = 10 $\overline{)5694}$

569 = half count

Readings at t_l = 54 (use original t_l setting and adjust trim)

New trim setting = 9
(obtain by trial and error)

1. 541
2. 555
3. 540
4. 580
5. 612

Sum 2828

Check = $\frac{\text{Sum}}{5}$ = 565

Figure B-18 Recalibration Data Sheet

the two beakers. If only a small portion of a sample is to be used, the smaller sample should be obtained by a number of splitting steps.

For example, if it is desired to use only 1/8 of a sample, split the original sample into two parts, split one of the new volumes into two additional parts and finally split one of the smaller volumes into two parts again.

6. Measure the orifice resistance with the counter unplugged.
7. Wash sample tube with distilled water prior to introducing a new sample.
8. Wipe orifice at least every fifth reading. Following each run, increase the armature current to the maximum, operate the system through two counting cycles and then make a final check on the 5μ range. This final check count is to be noted at the top of the data sheet.
9. The following number of repeats shall be made for each count:

Count	Repeats
10 - 100	8
100 - 1000	2
1000 - 6000	1

Counts should not exceed 10,000

Typical sampling data sheets are presented on the following pages. They are self-explanatory and are set up to provide the instrument operator who is familiar with the equipment a step by step analytical procedure for sample analysis.

Test I. D. 13-49

Probe Position 1C

Date 5-3-72

On Test Floor

Sample Flow Rate (A) 56 SCFM

Time (B) 5 Minutes

Sample gas volume (AxB) (C) 4.667 Cubic Feet

Final Isoton volume in impinger following particle collection and impinger wash (D) 300 ml

Initial Dilution and Test

Portion of sample used for initial dilution test (E) 25 ml

Isoton added for initial dilution test. (Note: Add sufficient Isoton to bring initial count down to 50,000 cts. Fluid will probably be cloudy but not opaque). (F) 175 ml

Total sample size for initial dilution test (E+F) (G) 200 ml

Initial counts

I = 1/8

A = 1/4

Trim = 6.5

t_l = 25

t_u = OFF

Matching Resistance = 20K

Figure B-19 Dilution and Volume Factor Summary Data Sheet (Probe C)

Counts for 50 μl (H) [illegible]
(I) [illegible]
(J) [illegible]

Sum (H + I + J) (K) [illegible]
Average $\left(\frac{K}{3}\right)$ (L) [illegible]

Dilution required $\left(\frac{L}{8000}\right)$ (M) 3

Note: round off to nearest unit (increase)

Selected sample size (N) 100
Dilutions added (O) 250
Total sample (N + O) (P) 350

Final Dilution

NOTE:

$$\text{If } (M) = \begin{bmatrix}1\\2\\3\\4\\5\\6\\7\\8\end{bmatrix} \text{ then set } (N) = \begin{bmatrix}150\\100\\50\\25\\25\\25\\25\\25\end{bmatrix} \text{ ml and } (O) = \begin{bmatrix}0\\100\\100\\75\\100\\125\\150\\175\end{bmatrix} \text{ ml}$$

The volume (gas represented by sampling volume (50 μl)) is:

$$V_s = E \times \frac{.05}{D} \times \frac{J}{L} \times \frac{N}{P}$$

Volume Factor Calculation

$$= 0.0167 \times \frac{.05}{800} \times \frac{28}{800} \times \frac{100}{850} = [illegible] \text{ cubic feet}$$

Figure 8-20 Dilution and Volume Factor Calculations Data Sheet (Probe C)

Single Threshold

70 μ Orifice

Isoton Electrolyte

Test I.D. 15-92

Probe Location 1C

Date 5-3-72

RT: 1:30 to 2:30

Sample Temp. 75.?

Aperture resistance 20 K

Matching resistance setting 20 k

Screening prior to test Y X N

Screen size 30 m

Background slider setting 896 / 816 / 855

Trio 6.16

Final count slider setting 10816, 10664, 10887
(Should match initial count)

Gain set at [illegible], Separate/Locked switch in separate

d	[illegible]	[illegible]	[illegible]	Count	Sum	Average
1.59	1/2	1/4	25	10836 [illegible] [illegible]	32551	10816
[illegible]	1/2	1/2	25	[illegible]	11029	3673
[illegible]	1/2	1	25	[illegible] [illegible] 2761	8799	2933
[illegible]	1/2	2	25	1287 [illegible] [illegible]	3798	1266
[illegible]	1/2	4	25	[illegible]	2164	541
[illegible]	1/2	8	25	[illegible]	602	151
[illegible]	1/2	16	25	[illegible]	262	53
[illegible]	1/2	32	25	[illegible]	59	7

Figure B-21 Raw Data Particle Count Data Sheet (Probe C)

Test I. D. 15-92

Probe Position 1B

Date 5-3-78

On Test Floor

Sample Flow Rate (A) 56 scfh

Time (B) 5 Minutes

Sample gas volume (AXB) (C) 4.667 Cubic Feet

Final Isotone volume in impinger following particle collection and impinger wash (D) 200 ml

Initial Dilution and Test

Portion of sample used for initial dilution test (E) 25 ml

Isoton added for initial dilution test. (Note: Add sufficient Isotone to bring initial count down to [illegible]. Fluid will probably be cloudy but not turbid.) (F) 175 ml

Total sample size for initial dilution test (E+F) (G) 200 ml

Initial counts

I = 90

A = 71

Time = 6.5

t_i = 25

t_p = 300

Resulting Dilution(s) = 80 x

Figure B-22 Dilution and Volume Factor Summary Data Sheet (Probe B)

Counts for 50 λ l (H) 15941
(I) 15876
(J) 15716

Sum (H + I + J) (K) 47533
Average $\left(\frac{K}{3}\right)$ (L) 15844

Final Dilution

Dilution required $\left(\frac{L}{8000}\right)$ (M) 2

Note: round off to nearest unit (upward)

Selected sample size (N) 100
Isotone added (O) 100
Total sample (N + O) (P) 200

NOTE:

$$\text{If } M = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{bmatrix} \text{ then set } N = \begin{bmatrix} 150 \\ 100 \\ 50 \\ 25 \\ 25 \\ 25 \\ 25 \\ 25 \end{bmatrix} \text{ ml and } O = \begin{bmatrix} 0 \\ 100 \\ 100 \\ 75 \\ 100 \\ 125 \\ 150 \\ 175 \end{bmatrix} = \text{ ml}$$

The volume (gas represented by sampling volume (50 λ l) is:

$$V_s = C \times \frac{.05}{D} \times \frac{E}{G} \times \frac{N}{P}$$

Volume Factor Calculation

$$= 4.661 \times \frac{.05}{300} \times \frac{25}{800} \times \frac{100}{200} = [illegible] \text{ cubic feet}$$

Figure B-23 Dilution and Volume Factor Calculations Data Sheet (Probe B)

Single Threshold

70 μ Orifice

Isotone Electrolyte

Test I.D. 13-42

Probe Location 1B

Date 5-3-72

ET: 1:30 & 2:30

Sample Temp. 23.5

Screening prior to test Y X N ___

Aperture resistance 20 K

Screen size 70 μ 276 [illegible]

Matching resistance setting 20 K

Background at 100μ setting 283

Trim 6.25

Final count on 1.44μ setting 8912, 9016, 8948
(Should match initial count)

Gain set at max., Separate/Locked switch to separate

μ	I	A	Si	Count	Sum	Average
1.44	1/16	1/4	25	[illegible]	27684	9228
2.44	1/4	1/8	25	[illegible]	10716	3572
3.14	1/8	1	25	1144 1133 [illegible]	3380	1127
3.96	1/8	2	25	342 [illegible] [illegible] 367	1418	355
5.0	1/8	4	25	101 [illegible] 96 95	387	97
6.3	1/8	8	25	[illegible]	176	22
7.92	1/8	16	25	[illegible]	56	7
10.0	1/8	32	25	[illegible]	32	4

Figure B-24 Raw Data Particle Count Data Sheet (Probe B)

Test I. D. 13-42

Probe Position 1A

Date 5-3-72

On Test Floor

Sample Flow Rate (A) 56 scfh

Time (B) 5 Minutes

Sample gas volume (AxB) (C) 4.667 Cubic feet

Final Isotone volume in impinger following particle collection and impinger wash (D) 300 ml

Initial Dilution and Test

Portion of sample used for initial dilution test (E) 50 ml

Isoton added for initial dilution test. (Note: Add sufficient Isotone to bring initial count down to 25,000 max. Fluid will probably be cloudy but not opaque). (F) 175 ml

Total sample size for initial dilution test (E+F) (G) 225 ml

Initial counts

I = 1/8

A = 1/4

Trim = 6.5

t_l = 25

t_u = MAX

Matching Resistance = 20 k

Figure B-25 Dilution and Volume Factor Summary Data Sheet (Probe A)

Counts for 50 λl (H) [illegible]
(I) [illegible]
(J) [illegible]
Sum (H + I + J) (K) [illegible]
Average $\left(\frac{K}{3}\right)$ (L) [illegible]

Final Dilution =

Dilution required $\left(\frac{L}{8000}\right)$ (M) 0

Note: round off to nearest unit [illegible]

Selected sample size (N) 225
Isotone added (O) 0
Total sample (N + O) (P) 225

NOTE:

$$\text{If } M = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{bmatrix} \text{ then set } N = \begin{bmatrix} 150 \\ 100 \\ 50 \\ 25 \\ 25 \\ 25 \\ 25 \\ 25 \end{bmatrix} \text{ ml and } O = \begin{bmatrix} 0 \\ 100 \\ 100 \\ 75 \\ 100 \\ 125 \\ 150 \\ 175 \end{bmatrix} \text{ ml}$$

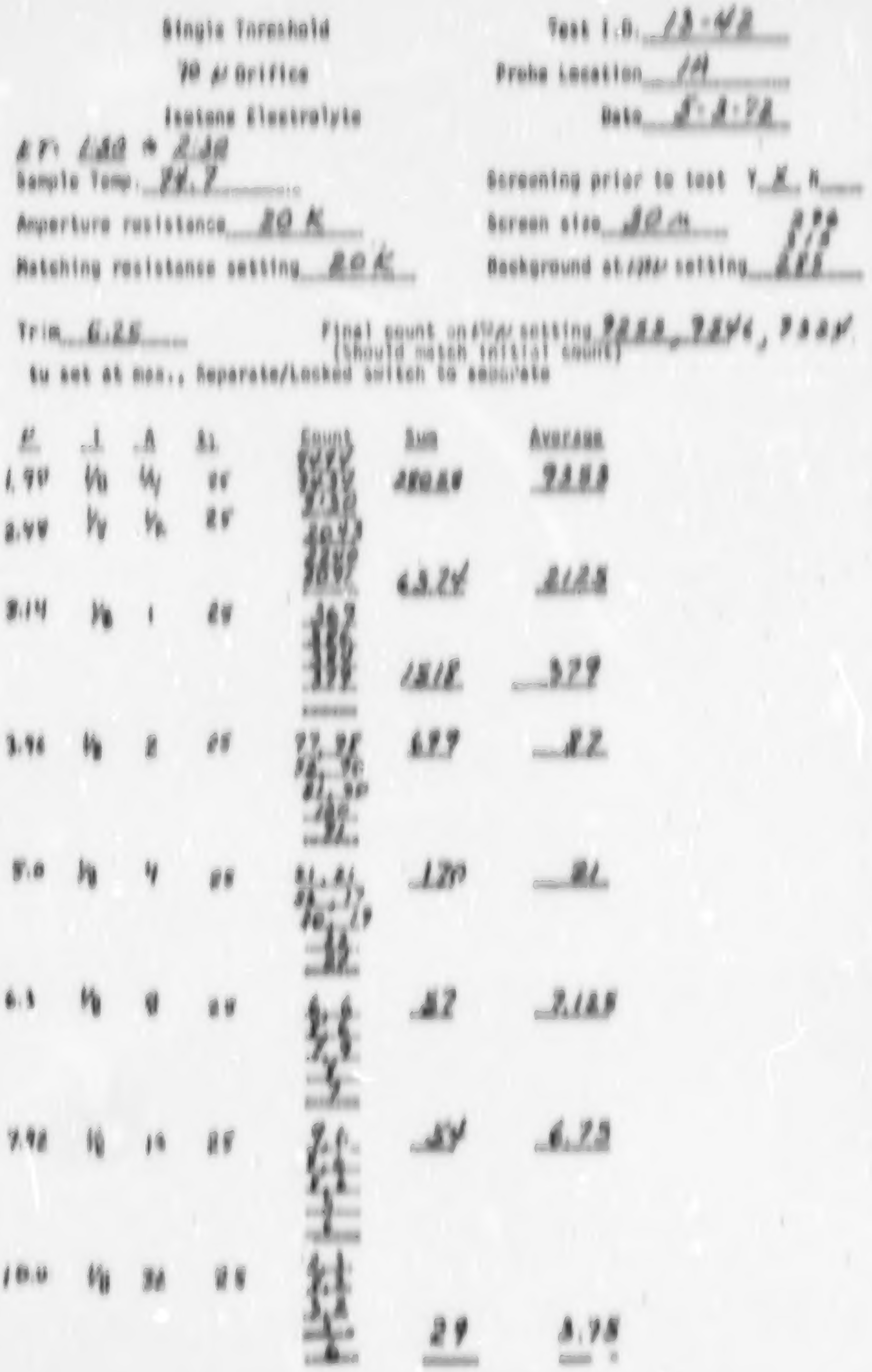
The volume (gas represented by sampling volume (50 λl) is:

$$V_s = C \times \frac{.05}{D} \times \frac{I}{E} \times \frac{N}{P}$$

Volume Factor Calculation

$$= [illegible] \times \frac{.05}{300} \times \frac{50}{225} \times \frac{225}{225} = [illegible] \text{ cubic feet}$$

Figure B-26 Dilution and Volume Factor Calculations Data Sheet (Probe A)



Single Threshold
70 μ Orifice
Isotone Electrolyte

Test I.D. 13-42
Probe Location 1A
Date 5-3-78

ΔT: 1:30 → 2:30
Sample Temp. 74.7
Aperture resistance 20 K
Matching resistance setting 20 K

Screening prior to test Y X N
Screen size 30 m
Background at 1.94μ setting 285

Trim 6.25
Final count on 1.94μ setting 9253, 9246, 9324
(Should match initial count)
Iu set at max., Separate/Locked switch to separate

μ	I	A	Δt	Count	Sum	Average
1.94	1/8	1/4	25	[illegible]	48068	9253
2.44	1/4	1/2	25	[illegible]	6324	2125
3.14	1/8	1	25	[illegible]	1518	379
3.96	1/8	2	25	77, 78 82, 76 81, 80 [illegible]	657	82
5.0	1/8	4	25	21, 21 [illegible]	170	21
6.3	1/8	8	25	6, 6 9, 6 7, 9 4	57	7.125
7.94	1/8	16	25	[illegible]	54	6.75
10.0	1/8	32	25	[illegible]	27	3.75

Figure 8-27 Raw Data Particle Count Data Sheet (Probe A)

Data Reduction-

The raw laboratory data is initially normalized to a standard gas volume (left hand side of sample Particle Counting Data Reduction Sheets, Figures B-28 and B-29). This is accomplished by multiplying the raw count by the ratio, selected unit volume to sample volume factor (noted on the laboratory data sheets). A preliminary distribution plot can then be generated from the normalized data (Figure B-30).

The data reduction from this point depends on the type of data required, single point loading, or particle removal system efficiency and loading. The following paragraphs describe the approach used for efficiency and loading evaluation. For single point loading analysis, the efficiency calculations are omitted and loading is directly calculated. However, the particle count curves should be reviewed to omit effects of coincidence and background.

Preliminary efficiency calculations - The preliminary efficiency calculations are used to correct the data for machine and procedural deficiencies. Efficiency is defined as the percent of particles removed by the separator or unit under test. Since this efficiency is dependent on particle size, it is not single values and must be expressed as a function of particle size.

The number of particles of a certain size entering the test unit is mathematically equivalent to:

$$= \left(\frac{dN_{in}}{d\mu}\right)_{\mu = \mu_a} (\Delta\mu) \Big|_{\Delta\mu \to 0} \qquad (5)$$

Test I. D. 13-42
Date 3-3-72
Upstream Probe 18
Downstream Probe 14

A) Upstream Sample Volume Factor [illegible] cubic feet.
B) Downstream Sample Volume Factor .0220 cubic feet.
C) Selected Base (Unit) Volume .01 cubic feet.
D) Δμ Selected for Analysis -1 microns.

	COUNT NORMALIZING	
(E)	(F)	(G) (PLOT)
μ	Upstream Raw Average Count Downstream Raw Average Count	Upstream Count/Unit V (F x C/A) Downstream Count/Unit V (F x C/B)
1.98	9228	4071531
	9353	541139
2.48	3572	734111
	2125	122946
3.14	1122	231640
	377	21928
3.96	355	73622
	87	5034
5.0	97	19956
	21	1215
6.3	22	4526
	7.125	412
7.92	7	1440
	6.15	390
10.0	4	823
	3.75	217

EFFICIENCY CALCULATIONS				
(H)	(I)	(J)	(K)	(L)
μ_s	μ_1	μ_2	η	$\eta_{average}$
2.0	1.98	2.48	56.10	56.10
2.5	1.98	2.48	74.21	74.74
2.5	2.48	3.14	75.27	
3.0	2.48	3.14	83.95	85.60
3.0	3.14	3.96	87.24	
4.0	3.14	3.96	91.33	91.90
4.0	3.96	5.0	92.47	
5.0	3.96	5.0	93.33	94.45
5.0	5.0	6.3	95.57	
6.0	5.0	6.3	93.94	96.30
6.0	6.3	7.92	99.65	
8.0	6.3	7.92	98.64	85.12
8.0	7.92	10.0	71.61	
10.0	7.92	10.0	72.36	72.36

Figure 8-28 Particle Counting Data Reduction Sheet (I)

Test I. D. 13-42
Date 5-5-78
Upstream Probe 1C
Downstream Probe 1B

A) Upstream Sample Volume Factor [illegible] cubic feet.
B) Downstream Sample Volume Factor [illegible] cubic feet.
C) Selected Base (Unit) Volume .01 cubic feet.
D) Δμ Selected for Analysis ________ microns.

COUNT NORMALIZING		
(E)	(F)	(G) (PLOT)
μ	Upstream Raw Average Count	Upstream Count/Unit V (F x C/A)
	Downstream Raw Average Count	Downstream Count/Unit V (F x C/B)
1.98	15814	2720763
	9228	1899351
2.48	6593	4663346
	3572	734811
3.14	2823	2564209
	1527	231296
3.96	1266	325583
	365	75028
5.0	541	135116
	97	19564
6.3	151	38722
	22	4546
7.92	33	8671
	7	1658
10.0	7	1836
	4	823

EFFICIENCY CALCULATIONS				
(H)	(I)	(J)	(K)	(L)
μ_o	μ_1	μ_2	η	$\eta_{Average}$
2.0	1.98	2.48	-.03	-.02
2.5	1.98	2.48	26.03	30.86
2.5	2.48	3.14	35.70	
3.0	2.48	3.14	40.09	47.83
3.0	3.14	3.96	56.26	
4.0	3.14	3.96	69.66	67.06
4.0	3.96	5.0	66.41	
5.0	3.96	5.0	78.08	81.70
5.0	5.0	6.3	85.31	
6.0	5.0	6.3	85.81	88.03
6.0	6.3	7.92	90.26	
8.0	6.3	7.92	86.99	90.37
8.0	7.92	10.0	93.13	
10.0	7.92	10.0	93.52	93.52

Figure 8-29 Particle Counting Data Reduction Sheet (2)

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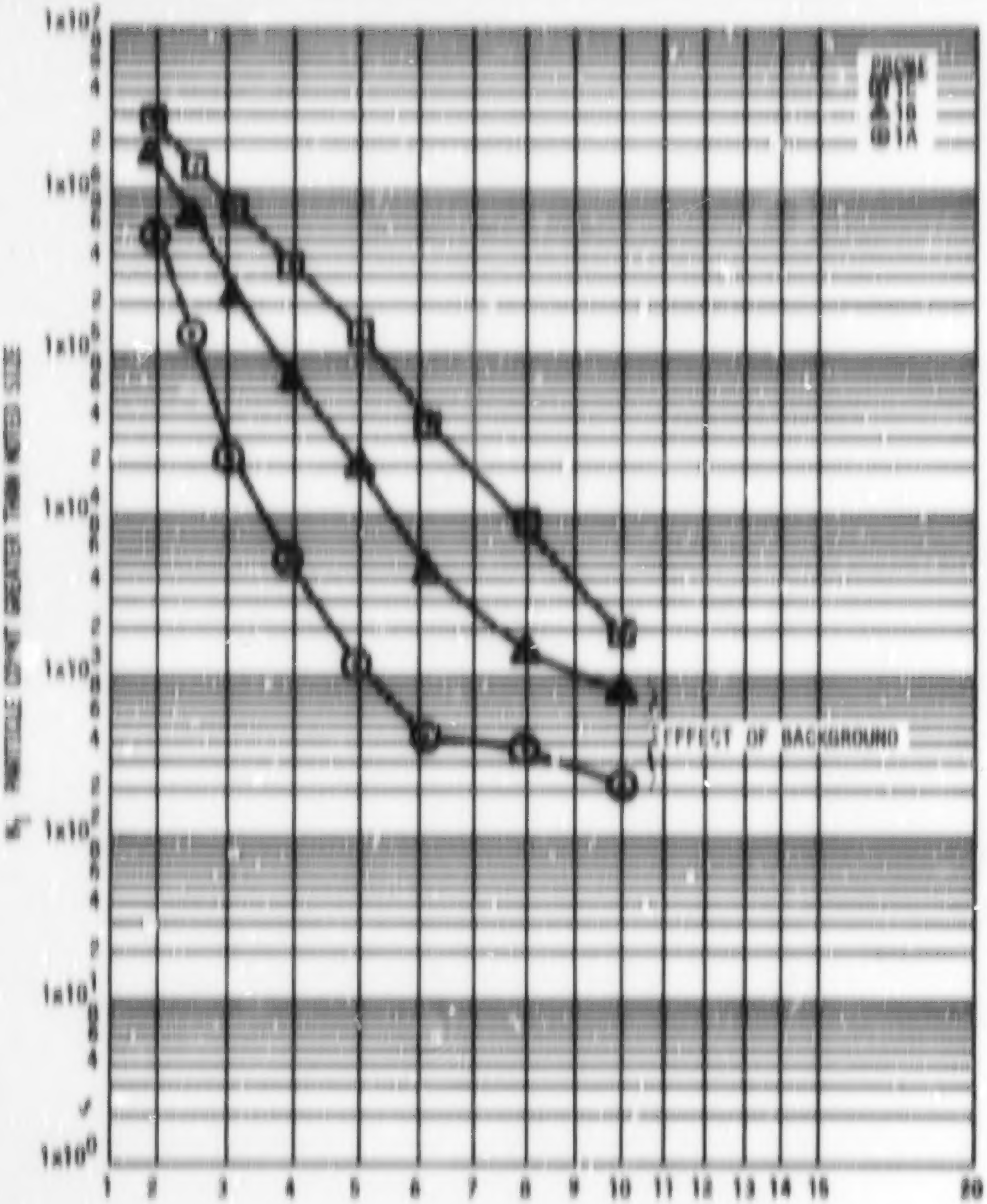

Figure 8-30 Preliminary Distribution Curves

where N is the number of particles greater than size μ. The number leaving the separator is equivalent to:

$$- \left(\frac{\underline{dN\ out}}{d\mu} \right) \mu = \mu_a \quad \left(\Delta\mu \right) \Bigg|\ \Delta\mu \rightarrow 0 \qquad (6)$$

The efficiency at μa (percent of particles of micron size μa removed by the separator) is therefore:

$$\underset{(\mu = \mu_a)}{\eta} = -100 \left\{ \frac{\dfrac{\underline{dN\ in}}{d\mu} - \dfrac{\underline{dN\ out}}{d\mu}}{\dfrac{\underline{dN\ in}}{d\mu}} \right\} \Bigg|\ \mu = \mu_a \qquad (7)$$

By selecting a sufficiently small micron size increment, the above expression can be approximated by:

$$\underset{(\mu = \mu_a)}{\eta} = 100 \left\{ \frac{\dfrac{\underline{\Delta N\ in}}{\Delta\mu} - \dfrac{\underline{\Delta N\ out}}{\Delta\mu}}{\dfrac{\underline{\Delta N\ in}}{\Delta\mu}} \right\} \Bigg|\ \mu = \mu_a \qquad (8)$$

$$= 100 \quad \frac{\Delta N\ in - \Delta N\ out}{\Delta N\ in} \Bigg|\ \mu = \mu_a \qquad (9)$$

where $\Delta N = \left\{ N(\mu = \mu_a - \mu) \right\} - \left\{ N(\mu = \mu_a + \Delta\mu) \right\} = -dN$ (10)

and N = number of particles greater than size μ

Assuming that the distribution tends to follow straight lines or straight line segments when plotted on log-log^2 paper, then:

$$\frac{\ln N - \ln N_1}{\ln N_1 - \ln N_2} = \frac{(\ln \mu)^2 - (\ln \mu_1)^2}{(\ln \mu_1)^2 - (\ln \mu_2)^2} \qquad (11)$$

where: N_x = number of particles larger than x

and: N_1, N_2, μ_1, and μ_2 are known from test results

This equation converts to:

$$N = \left[(N_1)(e^{a})\right]$$

where:

$$a = \frac{(\ln N_1 - \ln N_2)\ (\ln \mu)^2 - (\ln \mu_1)^2}{(\ln \mu_1)^2 - (\ln \mu_2)^2} \qquad (12)$$

Using formulas 9, 10, and 12 it is possible to determine the separator efficiency for any particle size using known input and output counts at two different particle sizes. Typical results are shown on the right side of the "Particle Counting Data Reduction Sheet". Note that in all but the extreme cases the efficiency at each selected micron size is determined using two different pair of data points. The dual answers are then averaged to compensate for non-linearity in the data. Also note that the calculation accuracy is dependent on the $\Delta\mu$ used in the calculation (equation 10). The $\Delta\mu$ selected should be small enough to provide accurate results and yet be sufficiently large to be compatible with the equipment used for the calculations. If it is too large, the approximation that $dN/d\mu = -\Delta N/\Delta\mu$ does not hold. If it is too large, the computational equipment will be unable to accurately determine the small differential (ΔN) between two large numbers.

Data compensation - The resulting efficiencies are next plotted on log-log paper (Figure 8-31). At this point, it becomes apparent where background influences have adversely affected the data. Assuming that the particles are essentially similar in shape and densities, inertial separator efficiency should continuously increase with particle size. However, when the count becomes small enough to be adversely influenced by background contamination, the apparent efficiency begins to decrease.

The effect of background count is illustrated in Figure 8-32 where the unprocessed laboratory readings are compared to a typical background distribution. At the two micron point, the background count is relatively low and introduces an error of approximately 3 percent. At the ten micron level, the background appears to be responsible for almost all of the counts for probes A and B. This large particle count results in a low apparent efficiency for the separator and must therefore be compensated for when reducing the data. Compensation is normally accomplished for inertial separators and similar devices by assuming a linear efficiency when plotted on log-log paper as illustrated in Figure 8-31.

Compensated distribution - Once the compensated efficiency curves are available, new particle distribution plots can be generated. The method used is to assume that the data for the highest loading (probe C) is most nearly correct (note that the background count has the least influence on this curve) and then calculate the other distributions based upon the corrected efficiencies.

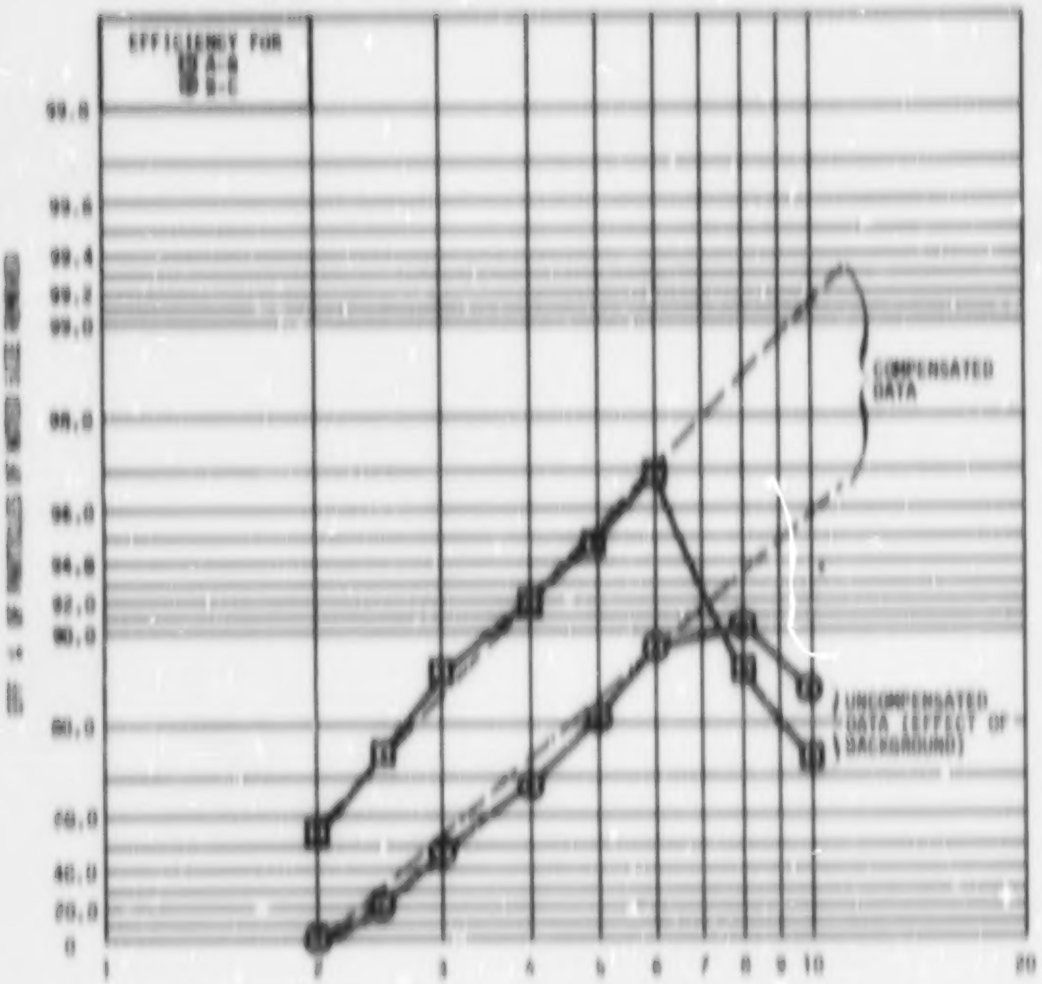

Figure B-21 Efficiency Curves

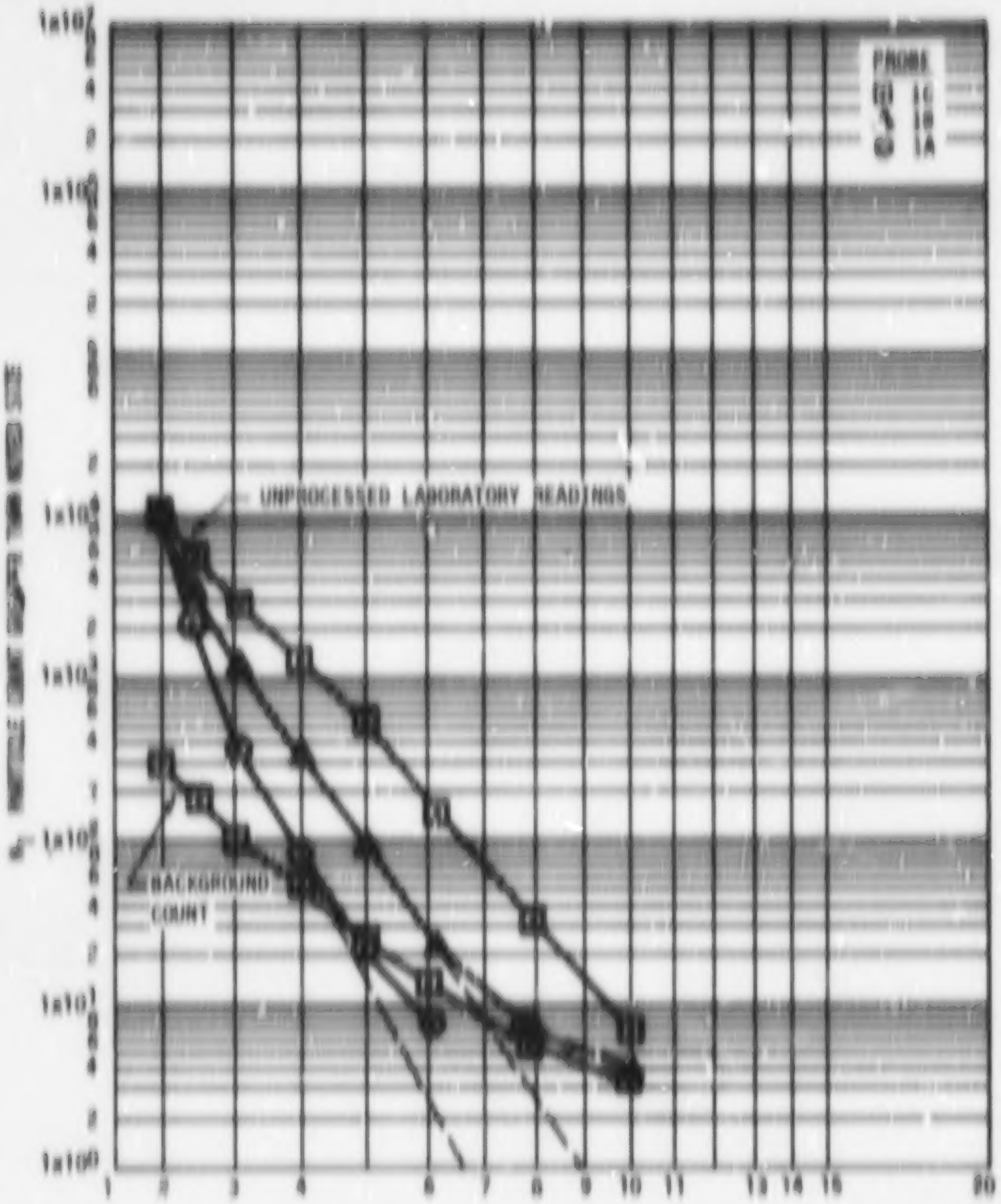

Figure B-32 Comparison with Background

From equation 10,

$$\frac{dN_{out}}{d\mu} = \left(1 - \frac{\eta}{100}\right) \frac{dN_{in}}{d\mu} \qquad (13)$$

or

$$N_{out} = \int \left(1 - \frac{\eta}{100}\right) \left(\frac{dN_{in}}{d\mu}\right) \; d\mu \qquad (14)$$

By assuming the plot of efficiency to be a straight line between points 1 and 2,

$$\left(1 - \frac{\eta}{100}\right) = \left(1 - \frac{\eta_1}{100}\right) \ln^{-1} \left\{ \frac{\ln\left(\frac{\mu}{\mu_1}\right)}{\ln\left(\frac{\mu_1}{\mu_2}\right)} \left[\ln \left[\frac{\left(1 - \frac{\eta_1}{100}\right)}{\left(1 - \frac{\eta_2}{100}\right)} \right] \right] \right\} \qquad (15)$$

where:

η_x = the efficiency for particles of size μ_x

By substituting the above into equation 14, selecting an appropriately small micron increment, and using the 2 micron count as the baseline, equation 14 can be approximated by:

$$\underset{\mu=\mu_a}{N_{out}} = \underset{\mu=2}{N_{out}} + \sum_{M=1}^{M = \frac{\mu_a + \Delta\mu - 2}{2\Delta\mu}} \left\{1 - \frac{\eta_1}{100}\right\} \left[\ln^{-1} \left\{ \frac{\ln\left(\frac{\mu}{\mu_1}\right)}{\ln\left(\frac{\mu_1}{\mu_2}\right)} \right\} \right] \left[\ln \left\{ \frac{\left(1 - \frac{\eta_1}{100}\right)}{\left(1 - \frac{\eta_2}{100}\right)} \right\} \right] \Delta N_{in} \qquad (16)$$

where:

$$\mu = 2 + 2M\,\Delta\mu - \Delta\mu \qquad (17)$$

$$\Delta N_{in} = \left\{ \underset{\mu=\mu+\Delta\mu}{(N_{in})} - \underset{\mu=\mu-\Delta\mu}{(N_{in})} \right\} \qquad (18)$$

A computer solution for the compensated curves using the example data is presented in Figure B-33.

Loading data - The particle loading is next determined from the distribution plot. Considering equation 18, N_{in} represents the number of particles within a $\pm \Delta\mu$ span about μ_a. Assuming that the typical particle is spherical and that the average volume of each particle is:

$$V_{particle} = \frac{\pi\mu^3}{6} \qquad (19)$$

The volume represented by the N_{in} particles is therefore:

$$V_{\mu = \mu_a \pm \Delta\mu} = \frac{\pi\mu^3}{6} \quad \Delta N_{in} \qquad (20)$$

The total volume of particles whose diameter is greater than μ_a is therefore:

$$V_{total} = \sum_{M=1}^{\infty} \left[\left(\frac{\pi\mu^3}{6} \right) \Delta N_{in} \right] \qquad (21)$$

where: $$\mu = \mu_a + 2M\Delta\mu - \Delta\mu \qquad (22)$$

By using an average density, d(grain/micron^{-3}), the total loading of particles greater than diameter μ_a is:

$$W = d \sum_{M=1}^{\infty} \left[\left(\frac{\pi\mu^3}{6} \right) \Delta N_{in} \right] \frac{\text{grains}}{\text{unit gas volume}} \qquad (23)$$

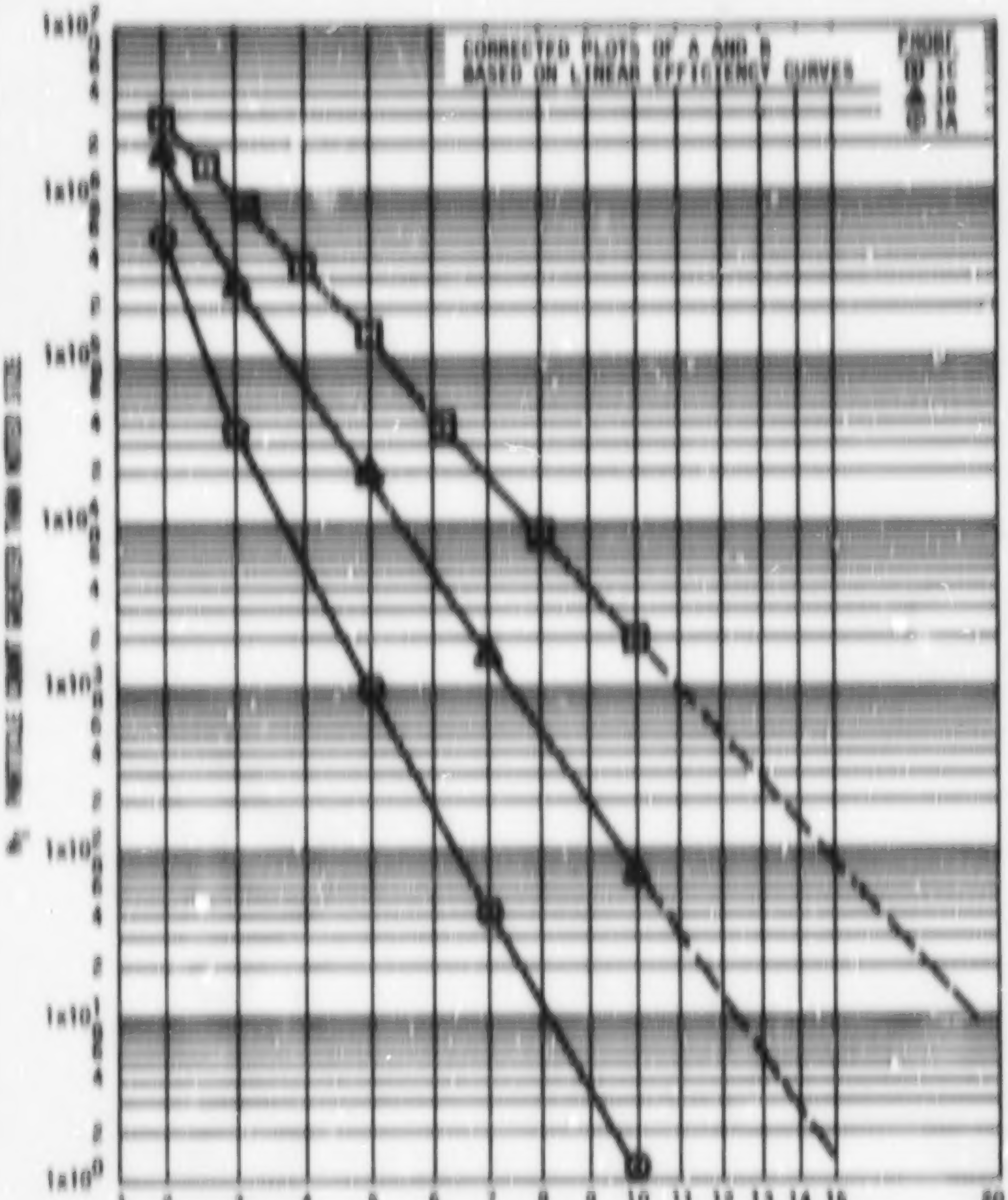

Figure 8-33 Compensated Distribution Curves

This expression has a limit as $M \to \infty$. Calculations will therefore indicate a particle point to cut off the summation. This is illustrated on the following calculation sheets for the example case.

Loading curves can be generated from the results as indicated in Figure 8-34. The total loading (determined by weighing all the particles in a collected sample) is plotted on the one micron line in order to show the limit for the loading curve.

Density calculation - The average density of the particles in the system can be determined using a dry collection of the particles, i.e., (sample of flyash from the test separator). This is accomplished by weighing the dry sample, mixing the weighed sample in a measured quantity of the analyzer solution and then proceeding through the complete analysis as though the sample were collected in the normal fashion. The weight of the particles counted by the analyzer is equal to the total dry weight multiplied by the ratio (volume drawn through analyzer to volume of sample solution). Calculation of the total volume of particles represented by the test sample is calculated using equation 21. Knowing the volume and weight, the average density can be calculated.

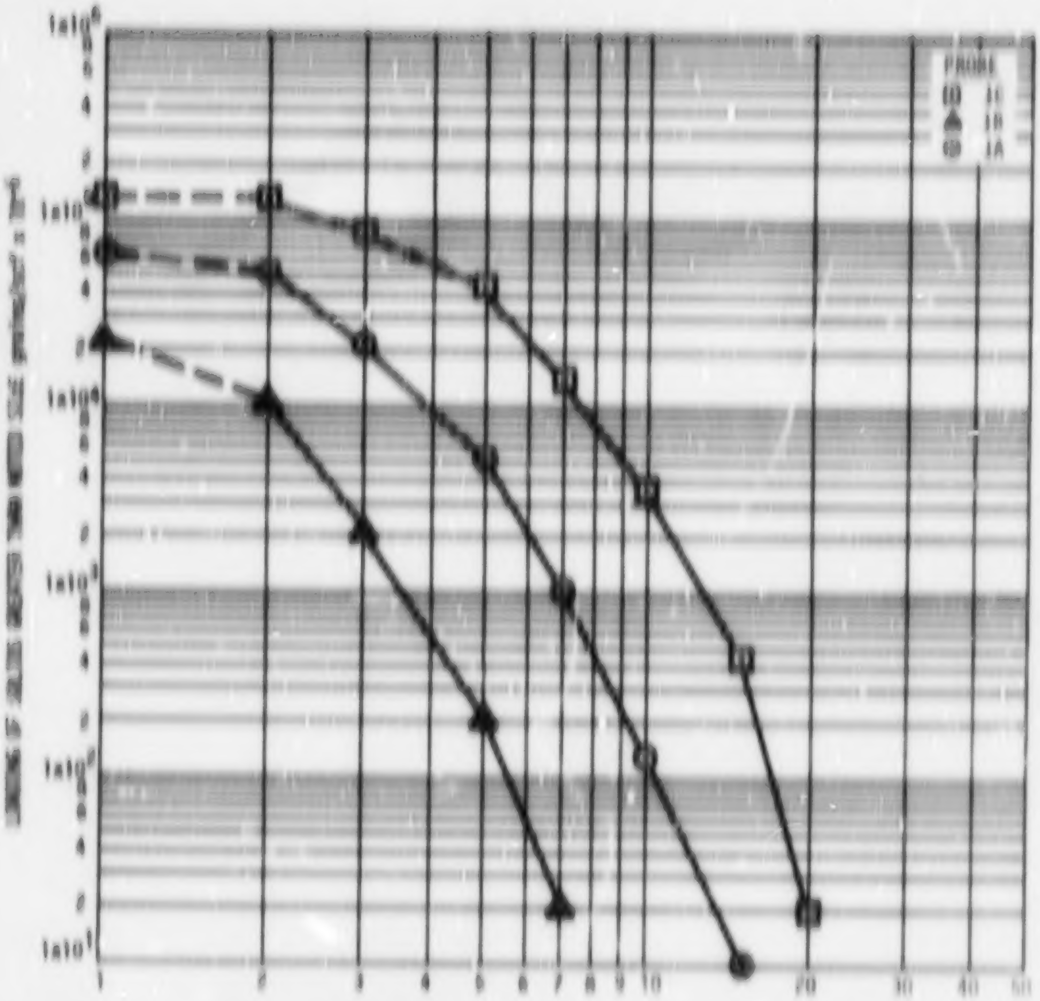

Figure B-34 Loading Curves.

Test I.D. 12-42
Date 3-3-72
Location 1st st. (C)

Total loading at the above location = .1233 grain/scf

Particle Size (μ)	Loading (grain/scf)
2<X≤3	.02670
3<X≤5	.04578
5<X≤7	.02871
7<X≤10	.01176
10<X≤15	.00326
15<X≤25	.00043
25<X≤40	.00003
40<X≤80	
80<X≤160	
160<X≤300	
300<X≤500	
500<X≤800	
800<X≤1200	
1200<X≤1600	

Total (X>5) .04419

Particle Size (μ)	Loading (grain/scf)	Weight %
X>2	.11667	
X>3	.08997	
X>5	.04419	
X>7	.01548	
X>10	.00372	
X>15	.00046	
X>25	.00003	
X>40		
X>80		
X>160		
X>300		
X>500		
X>800		
X>1200		

Loading of particulates equal or less than 5 μ = ______ grain/scf

wt % of particulates equal or less than 5 μ = ______ %

Figure B-35 Loading Analysis Sheet (Probe C)

Test I.D. 13-48
Date 5-3-78
Location 2nd st.(1R)

Total loading at the above location = .0668 grain/scf

Particle Size (μ)	Loading (grain/scf)
2<x≤3	.02995
3<x≤5	.01636
5<x≤7	.00423
7<x≤10	.00078
10<x≤15	.00013
15<x≤25	.00001
25<x≤40	
40<x≤60	
60<x≤100	
100<x≤200	
200<x≤500	
500<x≤800	
800<x≤1200	
1200<x≤1800	

Total (x ≥ 2) .0529

Particle Size (μ)	Loading (grain/scf)	weight %
x ≥ 2	.05150	
x ≥ 3	.02155	
x ≥ 5	.00587	
x ≥ 7	.00109	
x ≥ 10	.00014	
x ≥ 15	.00001	
x ≥ 25		
x ≥ 40		
x ≥ 60		
x ≥ 100		
x ≥ 200		
x ≥ 500		
x ≥ 800		
x ≥ 1200		

Loading of particulates equal or less than 2 μ = ____________ grain/scf

wt % of particulates equal or less than 2 μ = ____________ %

Figure B-36 Loading Analysis Sheet (Probe B)

Test I.D. 12-42
Date 3-3-78
Location 2nd out(1P)

Total loading at the above location = .0212 grain/scf

Particle Size (μ)	Loading (grain/scf)
2<X≤3	.00816
3<X≤5	.00195
5<X≤7	.00020
7<X≤10	.00002
10<X≤15	
15<X≤25	
25<X≤40	
40<X≤80	
80<X≤160	
160<X≤300	
300<X≤500	
500<X≤800	
800<X≤1000	
1000<X≤1500	

Total (X>5) .00022

Particle Size (μ)	Loading (grain/scf)	Weight %
X>2	.01033	
X>3	.00217	
X>5	.00022	
X>7	.00002	
X>10		
X>15		
X>25		
X>40		
X>80		
X>160		
X>300		
X>500		
X>800		
X>1000		

Loading of particulates equal or less than 5μ = ____________ grain/scf

wt % of particulates equal or less than 5μ = ____________ %

Figure B-37 Loading Analysis Sheet (Probe A)